Master Thesis, Department of Geosciences

Late Cenozoic evolution of the upper Bjørnøya Fan, western Barents Sea margin:

A seismic sequence stratigraphic analysis

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Abstract

The Bjørnøya Fan is located at the SW Barents Sea continental margin and consists of a succession of glaciomarine sediments up to 3.5 - 4 km in thickness. The evolution of the Bjørnøya Fan is closely related to the history of the Plio-Pleistocene northern hemisphere glaciations.

In the present master thesis, the seismic stratigraphy of the Bjørnøya Fan was divided into three major glaciomarine units (GI-GIII), seven megasequences (MS1- MS7) and 28 sequences (S1- S28). Relative chronology of the identified seismic sequences was done and their approximate ages constrained, based on published ages of the seven megasequences.

The seismic sequences are repeated through the whole Bjørnøya Fan. Each seismic sequence may hypothetically represent one glacial cycle. One individual glacial cycle is interpreted to be related to the advance of a glacier ice sheet to the continental shelf edge, followed by retreat, glacioeustatic sea level rise and deposition of interglacial mud or clay, before the next advance of glacial ice sheet of the new glaciation.

Variations in depositional processes resulted in shifts in depocenters through time. These changes reflect the evolution of the glaciomarine depositional environment in time and space. Within the Bjørnøya Fan, three stages of development can be marked, correlated to the three glaciomarine units GI-III. The three units represent three stages influenced by the northern hemisphere glaciations and their effect on the development of the SW Barents Sea continental shelf. The first stage is correlated to the initiation of glaciations in the Barents Sea continental shelf and represents a transition from pre-glacial to glacigenic sedimentation. The second stage, initiated at ~ 1.5 Ma ago, is characterized by distinct prograding clinoforms that are correlated to the onset of repeated major ice sheet expansion to the shelf edge. In the third stage, depositional conditions changed to be characterized by glacigenic debris flows that were sourced from a common and homogenous part of the upper part of the Bjønøya Fan.

The Bjørnøya Fan appears to have been repeatedly affected by altogether 28 glacial events, some of which may represent stadials, represented by the 28 seismic sequences.

It seems that the glacial history at several sites of the NE Atlantic margin is similar, revealing successions of about 30 possible glacial sequences or depositional units, representing glacial

cycles. The maximum number of glacial cycles can vary from place to place due to a number of factors, such as geological setting that influenced the effect of glaciations and preservation potential of glacigenic deposits on the continental shelf basins. In the present study the correlation between Iceland, the Mid-Norwegian continental shelf and the SW Barents Sea continental shelves were examined.

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Chapter 1: Introduction

During Cenozoic the NW Atlantic margin was affected by large-scale tectonics with the opening of the Norwegian-Greenland Sea and by the northern hemisphere glaciations. As a result to that, during the last 2.7 Ma, thick prograding sediment wedges were deposited, causing migration of a clastic shelf up to ~ 150 km basinwards into the Norwegian Sea (Dahlgren et al 2005). The Pleistocene shelf succession consists of a series of coalescing clastic systems of glacial origin, including several large submarine fans, together terminating in a shelf break, forming the morphological shelf edge along the passive continental margin of the European plate. One of the biggest fans in the NE Atlantic margin is the Bjørnøya Fan (Faleide et al. 1996, Vorren and Laberg 1997, Andreassen et al. 2004). It consists of 3.5-4 km thick succession of glaciomarine sediments (Fiedler and Faleide 1996). The development of the Bjørnøya Fan depicts the effects of the opening of the Norwegian- Greenland Sea and the northern hemisphere glaciations (Hjelstuen et al. 1996, Faleide et al. 1996, Fiedler and Faleide 1996). The opening of the Northern Atlantic caused uplift of the Barents Sea region (Dimakis et al. 1998, Faleide et al. 2008) that subsequently became the site of nucleation of very large ice caps during several glaciations (Eidvin et al. 1993). One major question related to the glacigenic, clastic shelf is how many individual glacial cycles that can be represented within the Plio-Pleistocene shelf succession. This is the main topic of the present master thesis study of the Bjørnøya Fan.

The Bjørnøya Fan is located at the southwestern margin of the Barents Sea shelf (Figure 1.1). The Barents Sea shelf extends from the North Atlantic and the Svalbard Archipelago in the west to Novaya Zemlya in the east. The western Barents Sea and Svalbard continental margin extends about 1000 km in a north-south direction (Faleide et al. 1996). The Barents Sea is towards the west bounded by its Cenozoic passive margins - formed during the final stages of North Atlantic break-up in the early Eocene (Barrére et al. 2009).

The evolution of the western Barents Sea is closely related to the opening of the Norwegian-Greenland Sea. In earliest Oligocene there was a shift in opening direction increasing the widening of the northern Greenland Sea (Faleide et al. 1996). Oceanic crust has been formed along the Barents Sea margins followed by subsidence of the area and creation of accommodation space for the deposition of a thick Late Cenozoic sedimentary wedge. Source areas were Barents shelf and Svalbard (Faleide et al. 1996). Based on the deep erosional channels related to the base of the large clastic wedge in the Bjørnøya area (Sættem et al. 1992) it is indicated that the ice margin was located very close to these localities as early as late Pliocene (Eidvin et al. 1993).

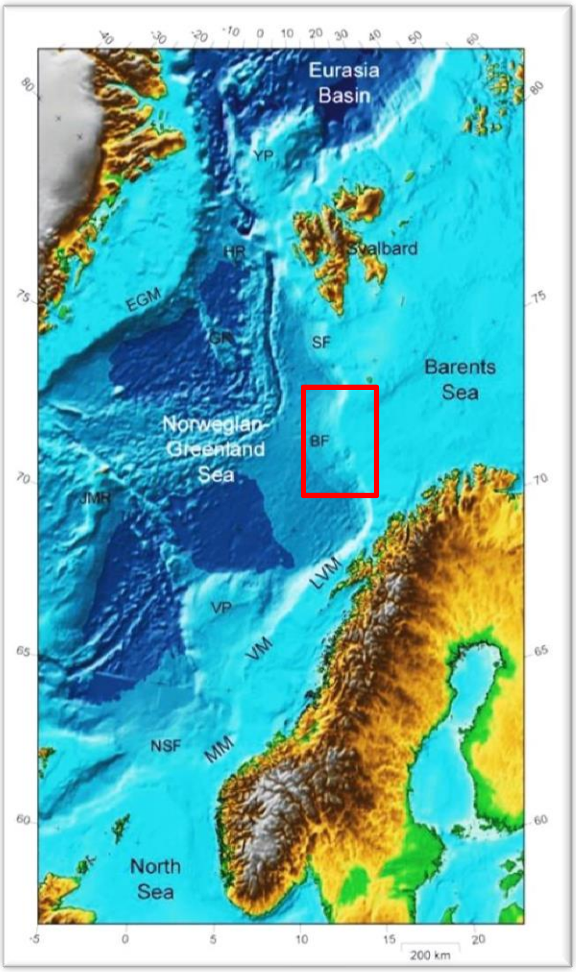

Figure 1.1.Regional setting of the Norwegian continental margin, which formed in response to the Cenozoic opening of the Norwegian-Greenland Sea. Bathymetry / topography from the 1× 1' elevation grid of Jakobsson et al. (2000). BF: Bjørnøya Fan, EGM: East Greenland Margin, GR: Greenland Ridge, HR: Hovgård Ridge, JMR: Jan Mayen Ridge, LVM: Lofoten-Vesterålen Margin, MM: Møre Margin, NSF: North Sea Fan, SF: Storfjorden Fan, VM: Vøring Margin, VP: Vøring Plateau, YP: Yermak Plateau. The Bjørnøya fan is bounded by the red rectangular (modified from Faleide et al. 2008).

The Barents Sea region is characterized by relatively shallow banks separated by deep troughs. The Bjørnøya and Storfjorden troughs, at the western margin, are the most prominent morphological features. The Sørvestsnaget Basin is separated from the Bjørnøya Basin by a Cenozoic normal fault system (Faleide et al. 1988). The Bjørnøya and Storfjorden troughs are both related to large submarine fans, reflected as seaward-convex bulges in the bathymetry. Their size is directly relating to the size of their trough and their drainage area relatively (Faleide et al. 1996, Laberg et al. 2012). Both the preglacial and glacial history is reflected in the present day topography of the Barents Sea region (Faleide et al. 1996, Ottensen et al. 2008, Andreassen and Winsborrow 2009, Laberg et al. 2012). The position of the Bjørnøya Fan is presented in Figure 1.1. During the late Cenozoic, at least five glacial advances reached the shelf break in the Bjørnøya Trough (Laberg and Vorren, 1995, Feleide et al. 1996, Mangerud et al. 1996).

As stated above, the main purpose of this thesis work is to study the late Cenozoic (Plio-Pleistocene) outbuilding on the upper Bjørnøya Fan and relate this to the glacial history of the NE Atlantic region. Detailed interpretation of 2D seismic data, sequence stratigraphic analysis and time-thickness mapping of the main seismic sequences within the Bjørnøya Fan will be the main tools of the present study. Correlation of the seismic sequence stratigraphy with the glacial history and the evolutional history between the source areas and the depocenters during late Cenozoic in the SW Barents Sea will be examined. Also a correlation between the study area and the Mid-Norwegian continental shelf and the Iceland will reveal the evolution of the northern hemisphere glaciation the last 2.7-3 Ma. This correlation will be mainly done by taking into consideration that each seismic sequence represents a glacial cycle,as the working hypothesis is that individual seismic sequences in the Bjørnøya Fan represents one glacial cycle.

The seismic sequences are repeated through the whole Bjørnøya Fan. This repetition, in terms of depositional environment, means that the deposition is related to the advance of ice sheets to the continental shelf edge, followed by retreat, glacioeustatic sea level rise and deposition of interglacial mud or clay, before the next advance of glacial ice sheet of the new glaciation. In addition to the main scope of the work, to rule out the maximum number of possible glacial events represented in the Bjørnøya Fan, the dynamic of the glacigenic depositional environment is also included as a part of the study.

Chapter 2: Geological setting of the SW Barents Sea

The Western Barents Sea was strongly affected by several rifting episodes during Late Paleozoic and Mesozoic. Three main extensional periods have been recognized: the first in Early – mid Carboniferous, the second one in Permian to early Triassic and the third in Late Jurassic- Early Cretaceous. (Faleide et al. 1993).Since Devonian, the Barents Sea region was influenced by at least five phases of basin development that resulted in crustal break up and sea-floor spreading of the North Atlantic rift zone.

According to Nøttvedt et al. (1992), in Ryseth et al. (2003), these five phases are:

i) Late Devonian- middle Carboniferous rifting,
ii) Late Carboniferous – Permian carbonate platform development,
iii) Triassic- Cretaceous siliciclastic shelf development,
iv) Early Cenozoic crustal break-up, and
v) Late Cenozoic passive margin development

Faleide et al. (1996) divided the Barents Sea and Svalbard continental margin into three main structural segments (Fig. 2.1):

1. a southern shared margin along the Senja Fracture Zone (70°-72°30'N)
2. a central rift complex associated with volcanism (72°30' -75°N) and
3. a northern initially shared, and later rifted, margin along the Hornsund Fault Zone (75° -80°N).

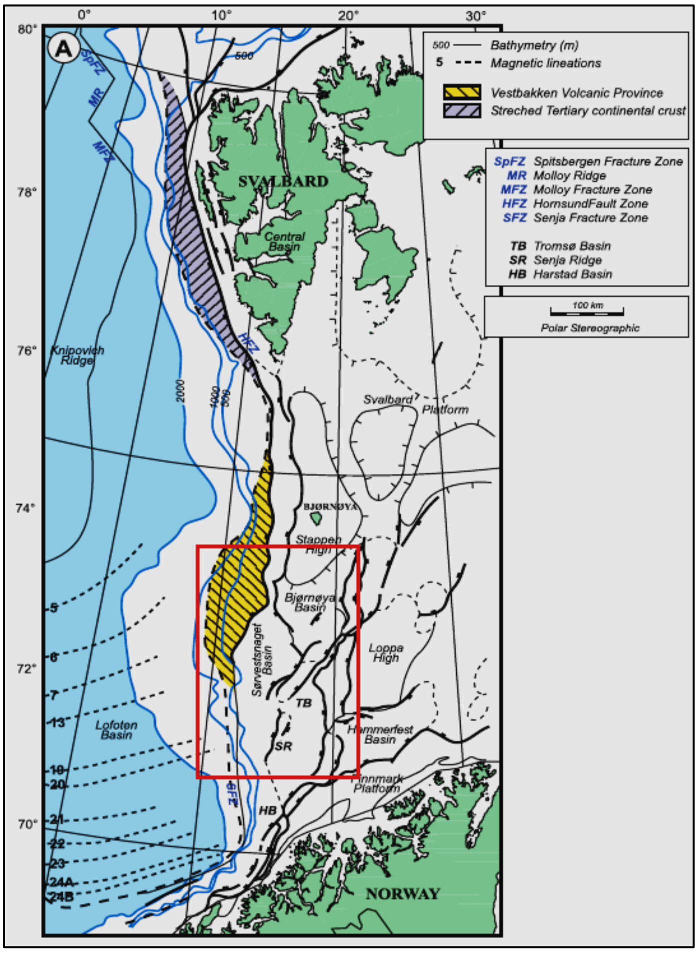

Figure 2.1.The main structural and plate tectonic features of the Barents Sea-Svalbard margin. (Feleide et al. 1996 modified by Ryseth et al. 2003)

The present-day topography of the Barents Sea (Figure 2.2) is influenced partly by the underlying bedrock and structural trends, but also by moulding by late Cenozoic glacial erosion (Faleide et al. 1996).According to Dimakis et al. (1998), the formation of fans like the Bjørnøya and Storfjordensubmarine fans requires very high erosion rates in the Barents Sea area. These high rates cannot be explained only by glacial processes. It requires that larger parts of the preglacial Barents Sea were subaerially exposed. The Barents Sea was partly glaciated and the rates of glacial erosion were varying, from less than ca. 0.15 mm/yr in areas that where least affected by ice streams and/ or glaciofluvial erosion. And more the ca, 0.6 mm/yr, corresponding to areas that experienced severe erosion from topographically confined ice streams (Laberg et al. 2012). According to Andreassen et al. 2007, more than 1000 m of berdorck has been eroded during the Cenozoic from the SE Barents Sea continental shelf. A major part of the erosion was glacial, caused by fast-flowing ice streams draining through Bjørnøya Trough to the shelf breaks (Andreassen et al. 2007). During relatively short periods of peak glaciations, grounded ice sheets extended to the shelf edge, transferring sediments and deposited debris at the margins at high rates (Dahlgren et al. 2002). This depositional system in the Barents Sea region was highly influenced by the interplay between erosion and uplift. Initial uplift was followed by intensive glacial erosion, counterbalanced by isostatic uplift leading to the preservation of an elevated and glaciated terrain. Thermal mechanism is the most likely explanation for the uplift observed in the Barents Sea (Dimakis et al. 1998).

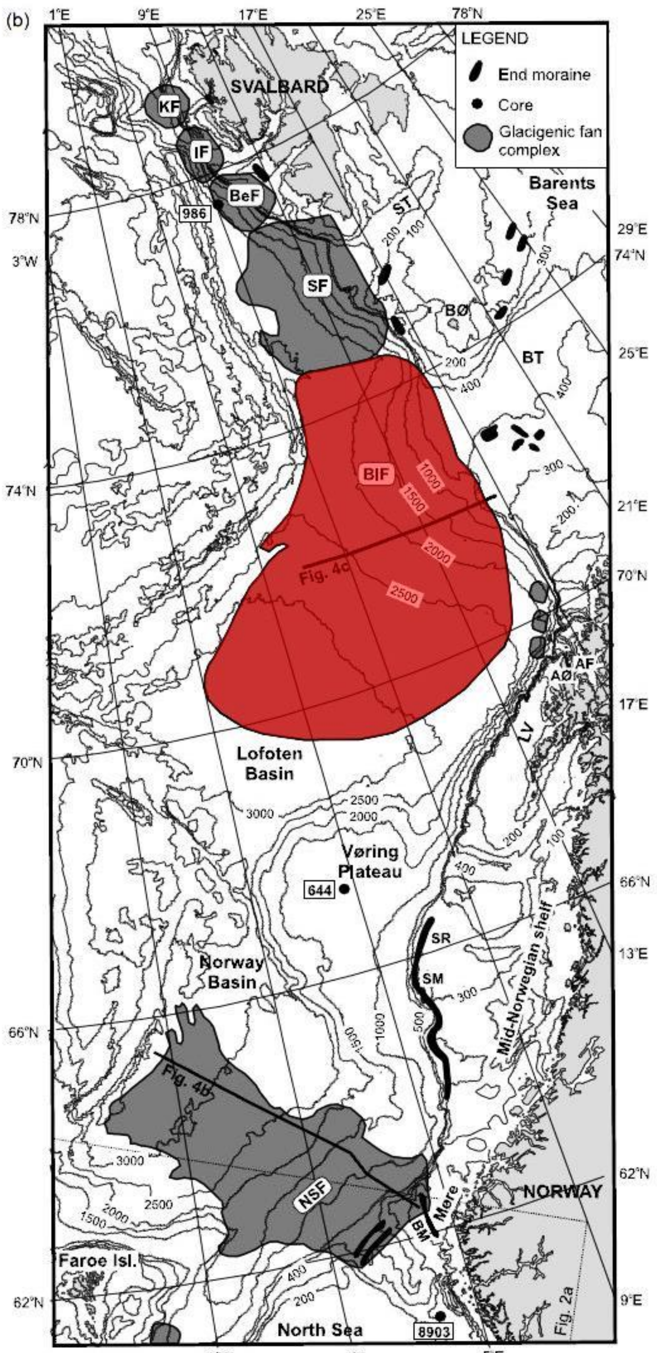

Figure 2.2.Detailed bathymetry (in meters) and physiography of the Norwegian-western Barents Sea-Svalbard continental margin. The Bjørnøya Fan is indicated by the red area. BT: The Bjørnøya Trough (Modified from Sejrup et al. 2005).

2.1 Glacial history of NE Atlantic margins

The main northern hemisphere glaciations are considered to have been initiated approximately 2.6 Ma ago (Thiede et al. 1989, Jansen and Sjøholm 1991 in Hjelstuen et al. 2007). A major indication for this interpretation was the marked influx of ice rafted detritus to the North Atlantic that started at this time. But also before that there are evidences of ice caps reaching the areas around the Norwegian-Greenland Sea from the Middle of Miocene (Figure2.3) (Fronval et al. 1996 in Hjelstuen et al. 2007).

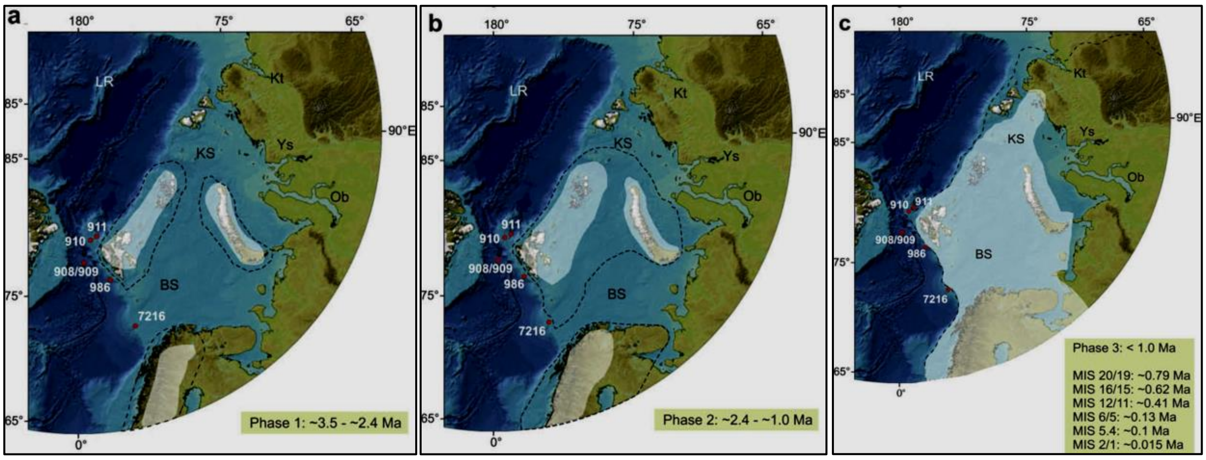

Figure 2.3. Schematic (min./max.) model of lateral ice extension in the Barents Sea region during the Late Plio-Pleistocene time period (black stippled lines ¼ maximum; white transparent polygons ¼ minimum): (a) Phase 1 (w3.5-2.4 Ma), (b) Phase 2 (w2.4-1.0 Ma). The style of glaciations during both phases is conceptual and based on data and reasoning discussed in the text, (c) Phase 3 (<1.0 Ma) is represented by the reconstructed Saalian (maximum) and LGM (minimum) glaciations (Svendsen et al., 2004). Major deglaciation periods subsequently to shelf edge glaciations are shown (according to Spielhagen et al., 2004; Knies et al., 2007b). (Modified from Kniest et al. 2009)

During the late Neogene the NE Atlantic margin was affected by sediment slides of variable scales and processes. The Western Barents Sea was also influenced by these processes. During the past 2.6 Ma, the high sedimentation rate due to northern hemisphere glaciations caused instable conditions in sediment accumulations along the margins that were exposed to high risk of mega-slides triggered by earthquakes or gas hydrate dissociation. One good example is the Bjørnøya Fan Slide Complex. Hjelstuen et al. (2007) documented that the mega-slide events started 1.0 Ma ago. The Bjørnøya Fan Slide Complex is consisting of 3 pre-Holocene mega slides (Figure2.4). The largest of those three (0.5-1.0 Ma) affected an area of 120 x 103 km^2 and involved about 25 x 103 km^3 of sediments (Hjelstuen et al. 2007). The Bjørnøya Fan Complex that is located in front of the Bjørnøya Trough is one of the many similar morphological features in NE Atlantic continental margins (Hjelstuen et al. 2007).

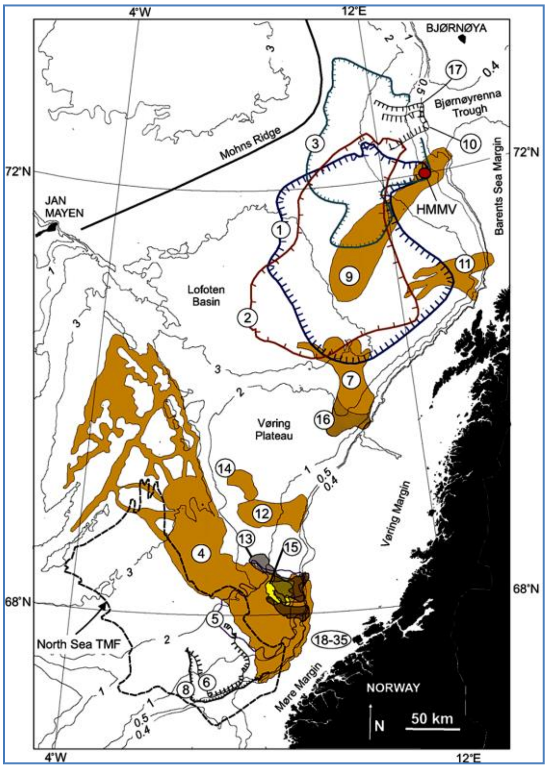

Figure 2.4.Location of Bjørnøya Fan Slide Complexes (I–III) and other slides along the NE Atlantic margin. Bathymetry in km. 1) BFSC II; 2) BFSC I; 3) BFSC III; 4) Storegga Slide; 5) Slide S; 6) Tampen Slide; 7) Trænadjupet Slide; 8) Møre Slide; 9) Bjørnøya Slide; 10) Slide A; 11) Andøya Slide; 12) Sklinnadjupet Slide; 13) Slide R; 14) Vigid Slide; 15) SlideW; 16) Nyk Slide; 17) Slide B; 18–35) A suite of minor slide (Hjelstuen et al. 2007)

2.2 Stratigraphy

The western margins of the Barents Sea are covered by thick Cenozoic fan deposits. Eidvin et al. (1993) proposed the age of the Bjørnøya Fan based on the wells 7117/9-1 and 7117/9-2 from the Senja Ridge, the well 7316/5-1 from the Vestbakken Volcanic Provinceand the well 7216/11-1 from the Sørvestsnaget Basin, and compared these results with stratigraphic data from well 7119/7-1 that is the closest well outside of the fan. The wells in Senja Ridge, Vestbakken Volcanic Province and Sørvestsnaget Basin are the only ones that penetrate the fan deposits. They concluded that the fan deposits are of glacial origin and that they were deposited in the Late Pliocene and Pleistocene. Based on the wells, the glacial sediments in SW Barents Sea are represented by lithostratigraphic units belonging to the Nordland Group (Worsley et al. 1988 in Dalland et al. 1988).

The ages of the Nordland Group are Late Pliocene to Pleistocene/Holocene in the Hammerfest Basin, extending back to the mid-Oligocene along western shelf margins. During this period the depositional environment was bathyal to glacial marine (Worsley et al. 1988 in Dalland et al. 1988).

The basal contact of glacial sediments with pre-glacial sediment is unconformable and represents an important depositional break in the latest Cretaceous and early Paleocene throughout the Tromsøflaket area (Worsley et al. 1988 in Dalland et al. 1988).

In the Mid-Norwegian continental shelf the glaciomarine sediments are part of the glacial Naust Formation that also belongs to Nordland Group (Worsley et al. 1988 in Dalland et al. 1988, Ottesen et al. 2009).

2.2.1 Pre-glacial sequences (Fiedler and Faleide 1996)

The pre-glacial sediments were divided into 4 sequences: Te1, Te2, Te3 and Te4 by Vorren et al. 1991.The distribution of the pre-glacial sediments has been influenced by the plate tectonic evolution of the Lofoten Basin and the uplift and erosion in the southwestern Barents Sea (Figure 2.5). The pre-glacial sequences pinch out eastwards towards the Senja Fracture zone (Fiedler and Faleide 1996).

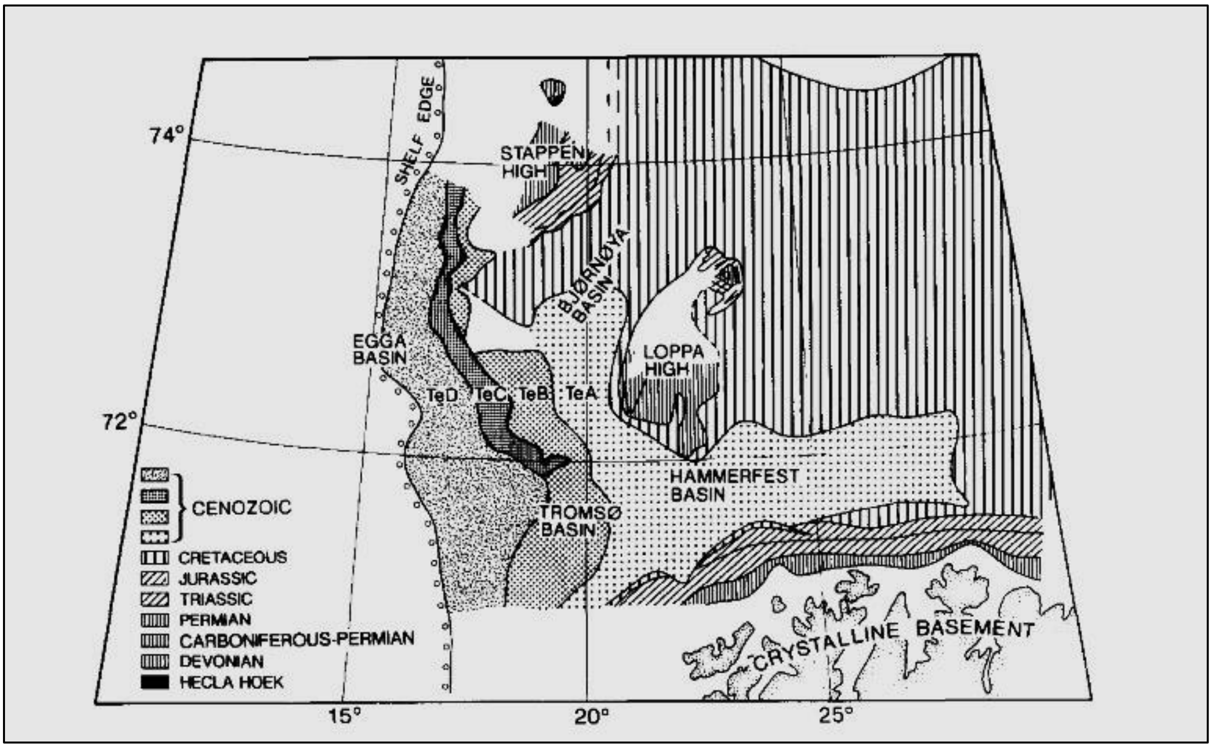

Figure 2.5.Subcrop map of the upper glacigenic diamicton. The map is based on data from this work and mapping by the Continental Shelf Institute, IKU (T. Bugge, personal communication.) The Tertiary subdivision is based on the seismostratigraphy used in this paper (Vorren et al. 1991)

The Te1 sequence has been deposited on the oceanic basement of Eocene aga in the Lofoten Basin and on early Eocene lava flow in the Vestbakken Volcanic Province. Its maximum thickness is observed proximal to the Senja Fracture Zone and in the Vestbakken Volcanic Province. The Te2 sequence was deposited on the oceanic basement of Oligocene age, in the area north of 72°N. The source area of Te2 sequence is located in the southwestern Barents Sea and in general Te2 is thinning in a southwards direction and finally pinches out at about 96°30'N. The Te3 sequence is the thickest of the 4 preglacial sequences. In the seismic, its lower boundary is a strong reflector that is characterized by high amplitude and good continuity. The Te4 sequence has it maximum thickness in the area around 72°N and is thinning towards the north and south. Its internal pattern is mainly characterized by transparent reflectors and in the slope area by prograding clinoform reflection configuration.

In general, the maximum thickness of the pre-glacial sediments is observed proximal to the continent-ocean transition at about 72°N (Figure 2.6). The distribution of the pre-glacial sediments probably has been affected by the lateral variation of the western Barents Sea margin during the early opening of the Norwegian- Greenland Sea. More specific, the opening of the Lofoten Basin during Eocene, resulted in the uplift of the continental crust along the Senja Fracture Zone, and the sediments from the erosion of the uplifted outer margin were mainly deposited east of the shelf (Faleide et al. 1993; Vågnes 1995). The pre-glacial sediments came mainly from the uplifted Stappen High surrounding Bjørnøya (Faleide et al. 1993).

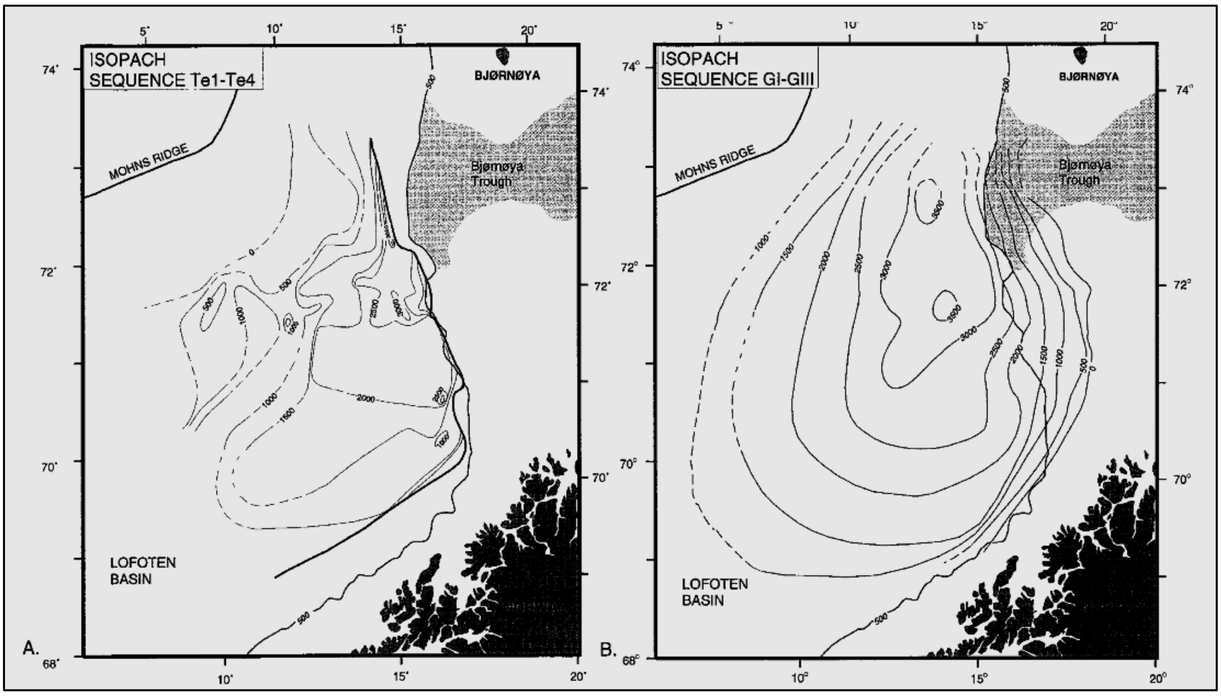

Figure 2.6.Isopach maps of the (A) pre-glacial deposits (Te1-Te4) and (B) the glacial deposits (sequences GI-GIII). Contour interval 500 m (Fiedler and faleide 1996).

Chapter 3: Methodology

3.1 Seismic Sequence Stratigraphy

Seismic sequence analysis is the seismic identification and interpretation of depositional sequences. It provides basic stratigraphic units that are both objectively defined seismically and, to a degree, predictable due to their relation to changes in relative sea level (Mitchum et al. 1977a).

Seismic facies analysis is the recognition and mapping of seismic facies units within seismic sequences, based on objectively defined seismic parameters such as reflection configuration, continuity, amplitude, frequency, and internal velocity. These seismic facies units may be interpreted in terms of environmental setting, depositional processes, and lithology estimations. A combination of seismic sequence analysis and seismic facies analysis is called seismic stratigraphy (Mitchum et al. 1977a). According to Mitchum et al. (1977a, p.117)"A seismic sequence is a depositional sequence (see Part 2, Vail et al. this volume) identified on a seismic section. It is a relatively conformable succession of reflections on a seismic section, interpreted as genetically related strata; this succession is bounded at its top and base by surfaces of discontinuity marked by reflection terminations and interpreted as unconformities or their correlative conformities. Seismic sequences have all the properties of depositional sequences subject only to the condition that these properties may be recognized and interpreted from the seismic reflection data."

In the present study, seismic stratigraphic sequence boundaries were applied. These were defined by prominent reflectors at the base between deposits revealing high acoustic impedance contrast combined with the concept of three main types of sequence boundaries: (1) that of Exxon by Mitchum (1977c) applying the subaerial unconformity (SU) and their correlative conformities in *depositional sequences*(2) that of Galloway (1989) using the maximum flooding surfaces (MFS) in *genetic stratigraphic sequences*, and (3) that of Embry and Johannessen (1992) applying trangressive surfaces (TS) in *trangressive-regressive (T-R) sequences* (Catuneanu et al. 2011, Enge 2008),all of these being stratigraphic sequences, orjust *sequences,* as the term used in this Thesis. The nature of seismic stratigraphic sequence boundaries, as represented by one or several of the SU, MFS and TS boundary types were determined by the type of reflection terminations (lapout) against the seismic boundaries (downlap, toplap and onlap) (Figure 3.1)(Mitchum et al. 1977a, Mitchum et al.1977b).

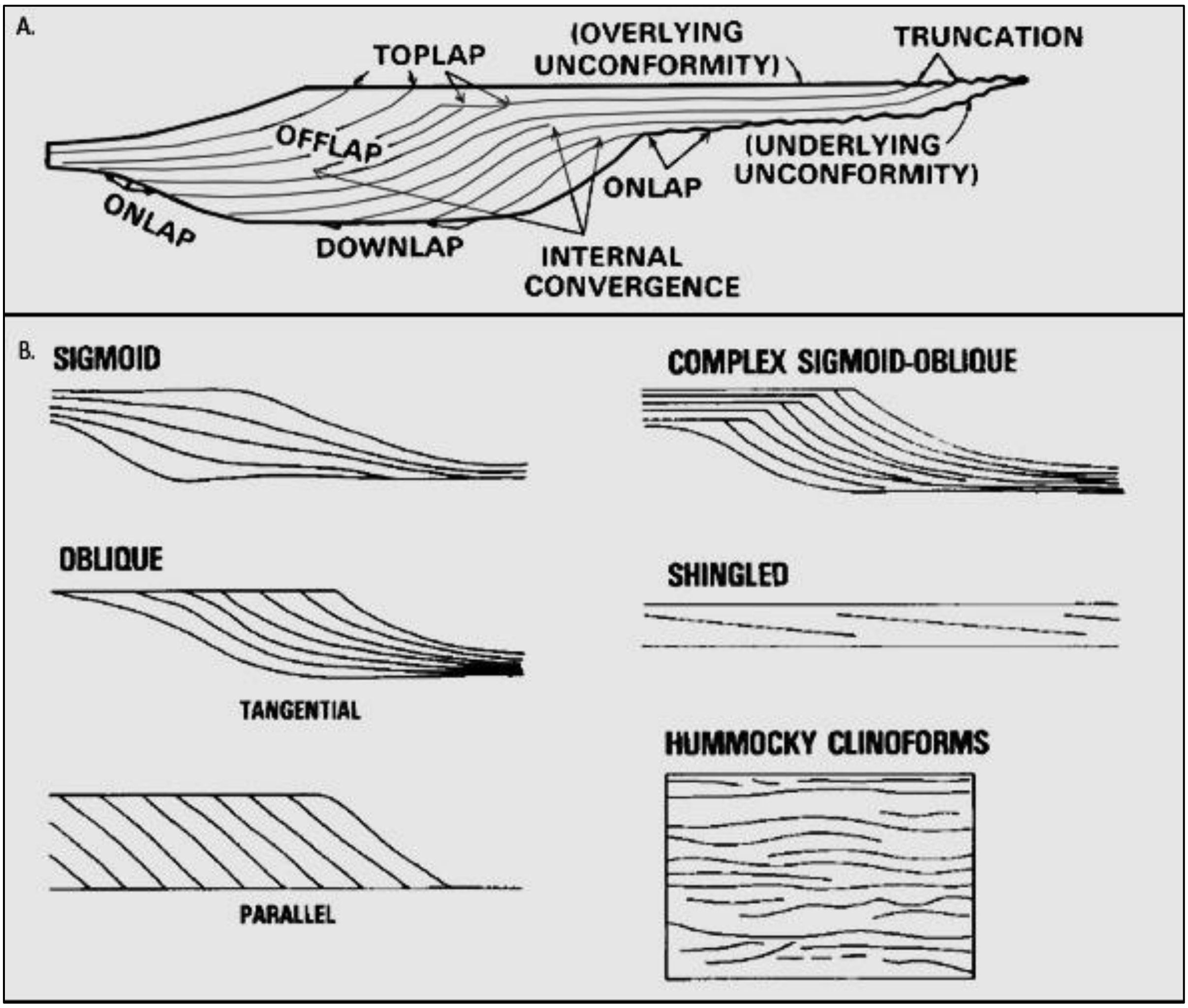

Figure 3.1.(A) Seismic stratigraphic reflection terminations within idealized seismic sequence (modified from Mitchum et al. 1977a). (B)Seismic reflection patterns interpreted as prograding clinoforms (modified from Mitchum et al. 1977a).

In glaciomarine depositional environments, the nature of seismic stratigraphic sequence boundaries can laterally change from MFS basinwards to regression surface landwards where the ice sheets have been grounding. (A subglacial unconformity, here termed a SGU, thus corresponds to the subaerial unconformity (SU) in the Exxon systematics.) The expression or not of this shift in character of the sequence boundary, as given in a seismic section, will be determined by the seismic resolution of the available seismic data set. For that reason, the quality of seismic interpretation is highly affected by seismic resolution. According to Sheriff (1991, p.1) “Resolution is the ability to separate two features that are very close together; the minimum separation of two bodies before their individual identities are lost."

An accurate definition and correlation of a depositional sequence (or stratigraphic sequence in general) can be achieved by marking first the sequence boundary at the base of the seismic sequence. The acoustic impedance contrast between beds above and below the unconformity and along the unconformity will determine the seismic expression of the seismic stratigraphic sequence boundary. For example, in glacial and interglacial successions the boundary between relatively dense glaciomarine till material and the overlying interglacial mud to hemipelagic clays of lower density will be expressed by high impedance contrast between the adjacent bedsets. In addition to that, sediment deposits in the base of a floating ice sheet will be characterized by different compaction from sediments that are at the base of a grounding ice sheet. In the case of the grounding ice the sediments will be overcompacted because of the extra weight of the ice sheet. These differences in compaction will be expressed also as differences in acoustic impedance contrast.

According to Gilbert (1985), Barrell(1912) and Rich (1951) clinoforms are seaward dipping surfaces, defined by the palaeo-depositional surface in shallow marine and shelf slope systems. Clinothems are the basinward dipping beds that are bounded be clinoforms (Rich 1951). A variety of factors such as the grain size of the sediment, the sediment distribution and the interplay of different depositional processes and the accommodation space can affect the gradient of the clinoform surfaces and the thickness and character of the clinothems associated with them (Orton and Reading 1993, Reading and Levell 1996 in Enge 2008). The clinoform geometry is also influenced by the relative sea-level and the gradient of the sea-floor during deposition (Posamentier and Morris 2000 in Enge 2008). Accommodation space is the space below base level (the level above which erosion occur) available for potential accumulation. On the continental margin, the base level is generally controlled by sea level (Jervey 1988).

Vertical stacking pattern of depositional unit (sequences, parasequences, clinothems, etc) can be progradational, retrogradational and aggradational (Fig. 3.2) (Emery and Myers 1996).

- Progradational stacking pattern occurs when sediment supply exceeds the rate of creation of topset accommodation space. In that case the facies at the top of each parasequence become progressively more proximal higher in the succession (Emery and Myers 1996).

- Aggradational stacking pattern occurs when the sediment supply and the rate of creation of topset accommodation volume are roughly balanced. In that case the facies at the top of each parasequence is similar (Emery and Myers 1996).
- In a retrogradational stacking pattern the facies become upward more distal (Emery and Myers 1996).

After having defined seismic sequences, seismic facies analysis is the next step in the work flow. With this method, environment and lithofacies within the sequences are interpreted from seismic and geological data. Reflection configuration reveals informations about depositional processes, erosion and paleotopography (Mitchum et al. 1977a).

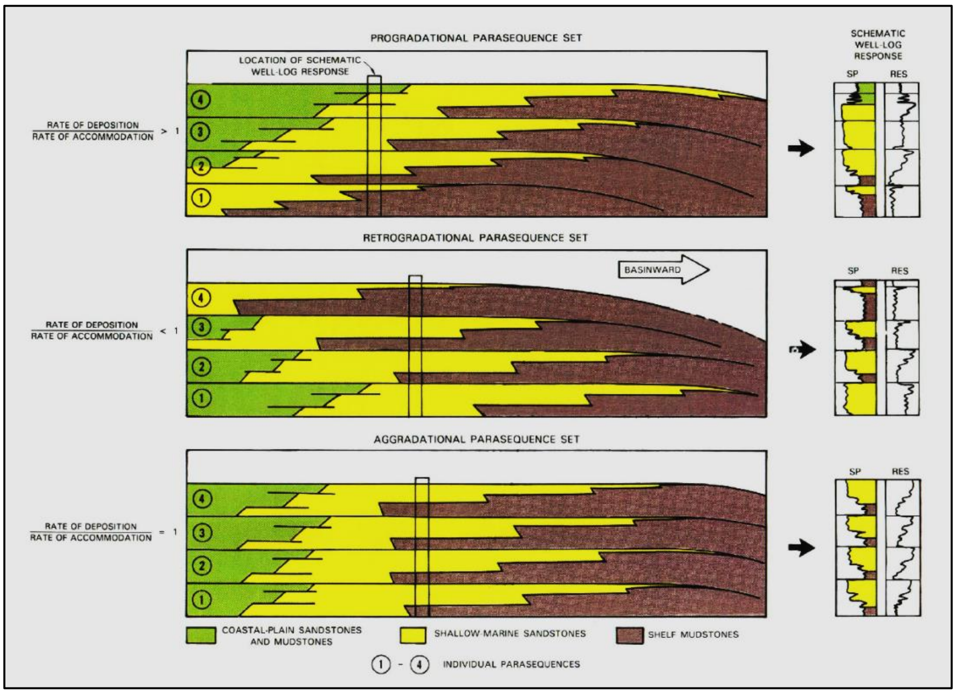

Figure 3.2. The three stacking patterns: Progradational, Retrogradational and Aggradational (Van Wagoner et al. 1988)

3.2 Workflow

This Master Thesis is based on a 2-D seismic data that is comprised of 168 seismic lines located in the area that the Bjørnøya Fan covers in the southwerstern Barents Sea (Fig. 3.3). From this 2-D seismic data set, 105 seismic lines were interpreted. For the seismic interpretation the Petrel Software 2012 by Schlumberger was used.

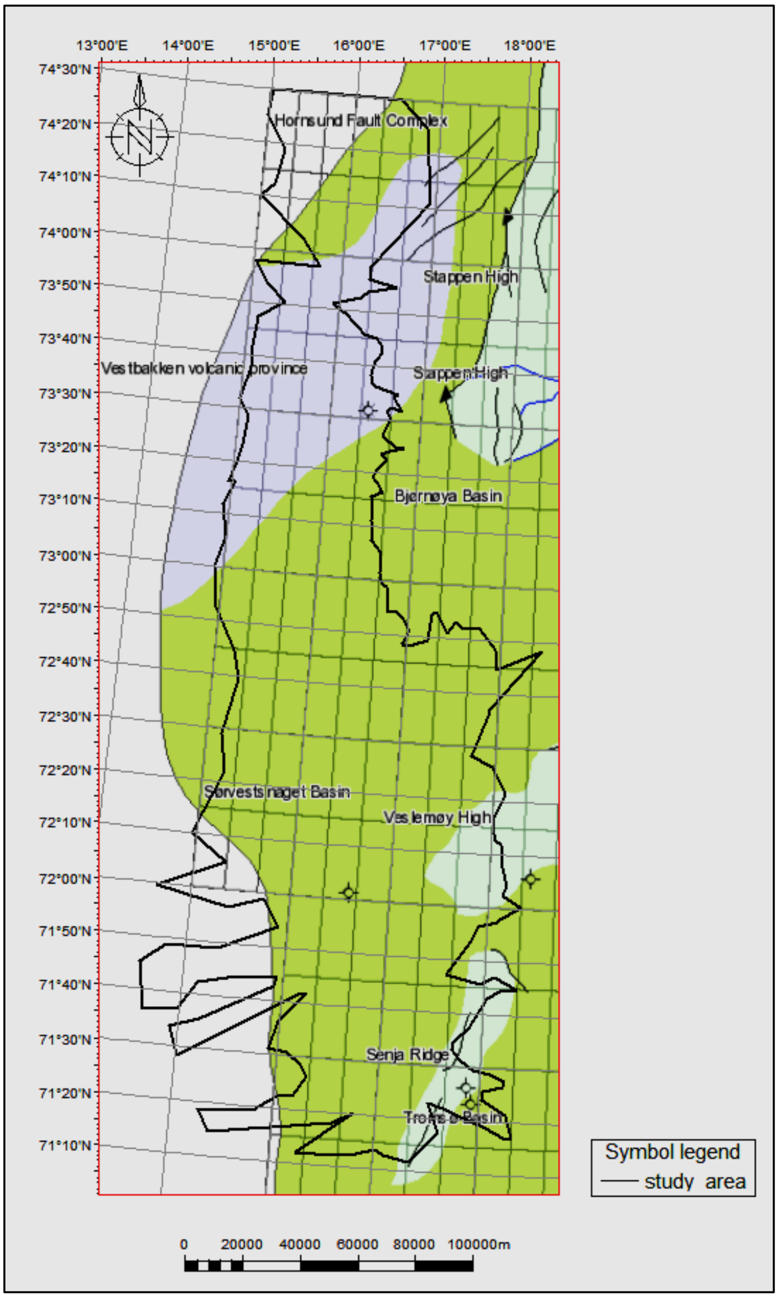

Figure 3.3. Study area is bounded by the black polygon. The map is from NPD.

The reasons for not making interpretation of the other seismic lines are:

- Mass slides have caused chaotic to structureless reflection configuration in some places, especially in the western part of the study area. In these locations no interpretation of the original depositional stratigraphy can be performed.
- The quality of some of the seismic lines did not help to facies analysis. There were locations where the internal structures of sequences could not be identified and only the sequence boundaries could be marked.
- In basinward areas the reflectors in the glaciomarine sediments tend to become subparallel to parallel. In these areas it is more difficult for subdivision of the megasequences.

In the study area 8 wells have been drilled, but informations were available only for 6 wells (Fig. 3.4). The started point for the seismic interpretation was the seismic line that runs through well 7216/11-1 S.

Figure 3.4.Wells in the study area. The map is from NPD.

Following steps were followed in the seismic interpretation work:

- Sequenced boundaries were defined and marked by using seismic reflection terminations.
- Based on the observations of the seismic lines and the previous literature the glaciomarine sediments were divided into 3 glaciomarine units (GI, GII and GIII) and 7 megasequences (S7-S1). The megasequences were subdivided into 29 sequences.
- From the marked sequence boundaries, time-thickness maps for the glaciomarine units GI-GII and the megasequence S7-S1 were made.
- Seismic facies analysis took place.
- Based on seismic interpretation of the 2-D data set a correlation between the deposition of the sequences and the different glacial cycles that affected the study area was made.

Chapter 4: Observations of the Seismic Data Set

In the past, a number of studies have been done in the Bjørnøya Fan. According to these, the Bjørnøya Fan has been divided into several seismic sequences. More specifically, the distribution of the Bjørnøya Fan has been defined seismically by the thickness of sediments between the bottom of the fan (R7) and the upper regional unconformity (URU).The URU name was first used by Henriksen and Vorren (1996) in the mid- Norwegian continental shelf. This unconformity truncates the R7 sequence boundary towards the east, defining the eastern boundary of the fan (Eidvin et al. 1993).

Based on literature, in the Bjørnøya Fan three glacial units have been identified: GI, GII and GIII. Within the glaciomarine sediments seven sequence boundaries have been identified (R1-R7). GI is bounded by the R7 and R5 sequence boundaries; GII is bounded by R5 and R1 (URU); and GIII unit is bounded at its base by R1 and at its top by the sea bed (Faleide et al. 1996, Fiedler and Faleide 1996).

The R5 sequence boundary is the boundary between the GI and GII glacial units. The shift from GI to GII marks a significant change in the depositional pattern. Above R5, the reflection pattern indicates large-scale sediment sliding into the deep sea basin to the west (Fiedler and Faleide 1996).

In the current study it was identified and marked three glaciomarine units (GI, GII and GIII). These units were subdivided into seven megasequences separated by the eight boundaries referred also in literature as R1- R7. The megasequences were further divided into sequences. The glacial units and the megasequences can be identified within the whole study area. The number of identified sequences varies significantly with the study area. It has been observed that in localities where the megasequences are thick, the number of the identified sequences is higher. In Figure 4.1 the identified and interpreted sequence boundaries in the present study are correlated with sequence boundaries published in the literature.

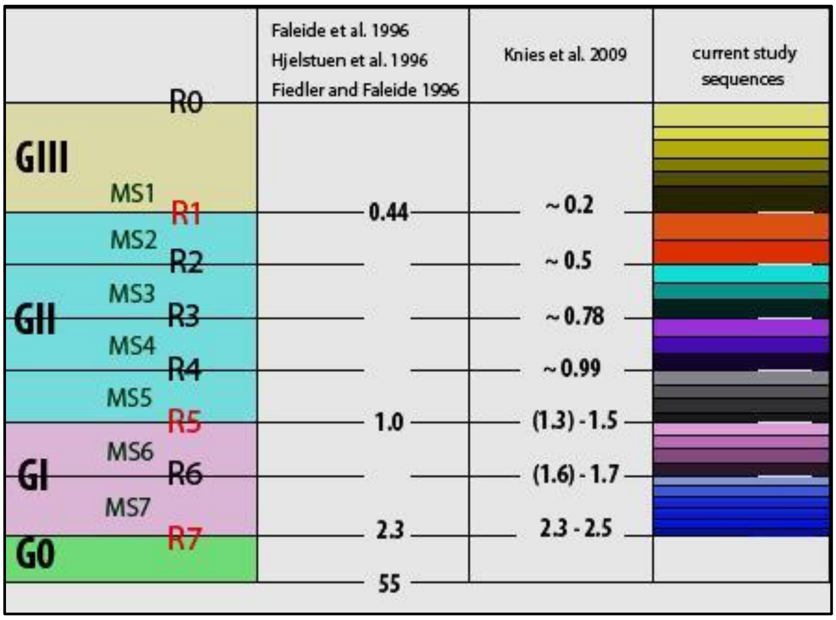

Figure 4.1.Correlation table of the identified and interpreted sequence boundaries within the Bjørnøya Fan with the literature.

The seven sequence boundaries divide the glaciomarine sediments into 7 megasequences (MS1- MS7). The R7 is the lowest boundary of seismic interpretation and sea bed (R0) the uppermost boundary. The R1 represents the URU and the R7 the regional downlap surface (RDS) that represents the base of the glacial sediments. The R7 is a strong reflector because of the high acoustic impedance contrast between glacial sediment and the underlying clay-rich Miocene strata (Reemst et al. 1996).

The main three glaciomarine units are divided into megasequences. The GI is divided into the MS7 and MS6 megasequences, the GII into the MS5- MS2 and the GIII unit is equivalent to the GI megasequence. For this paragraph five key profiles were selected in order to present the main pattern of each glaciomarine unit. The location of each key profile is displayed in Figure 4.2.

For each key profile three different versions are presented: (i) the section without interpretation, (ii) the section with the megasequence boundaries displayed and (iii) the section with the three glaciomarine sequences highlighted. In general, in all key profiles the glaciomarine sediments are divided into all of the three glaciomarine units GI, GII and GIII. The GI is divided into two megasequences MS7 and MS6. The GII is divided into four megasequences, M5 to MS2, and the GIII into one megasequence, MS1. The observations that were made in seven key seismic sections are presented below.

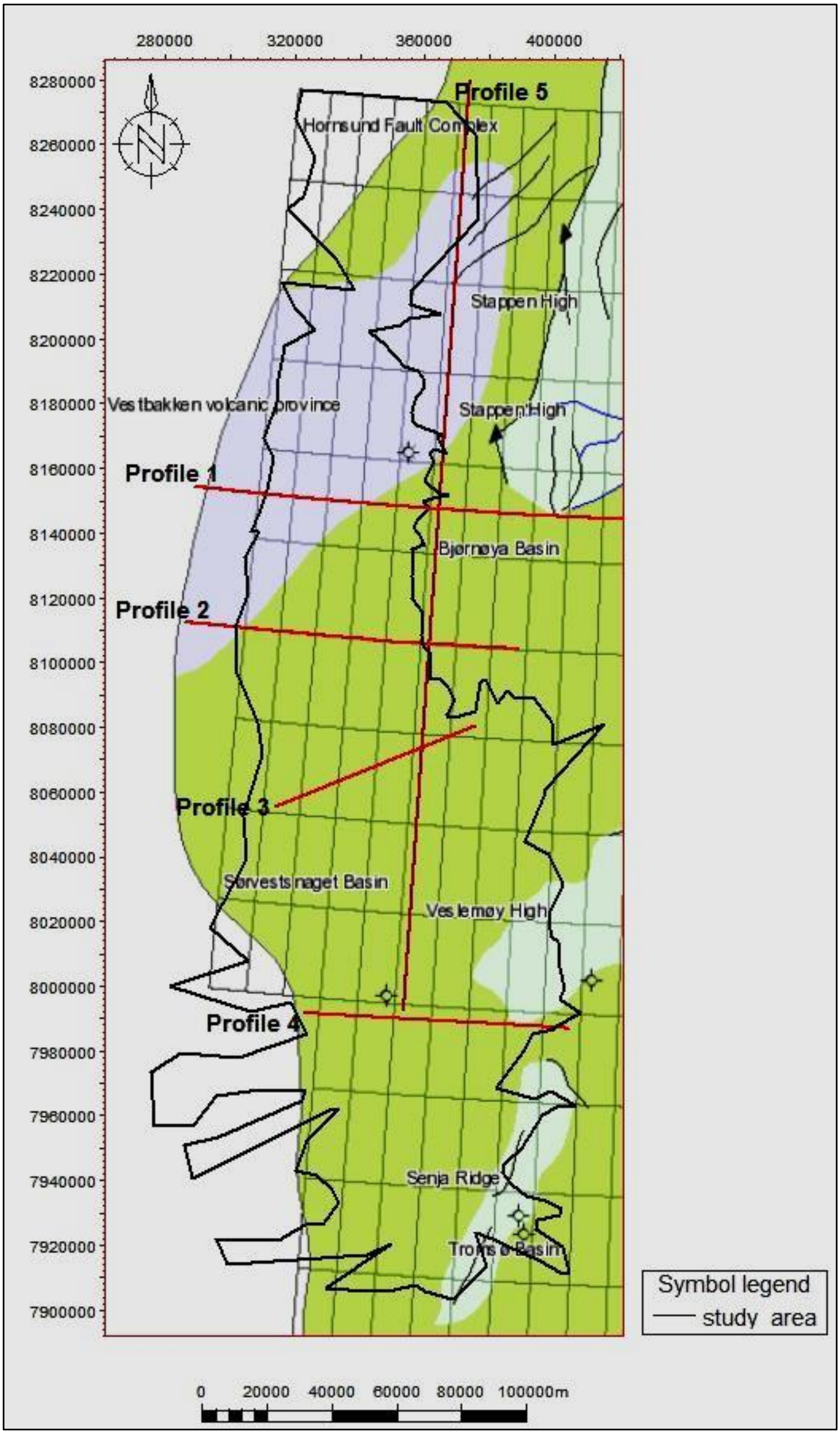

Figure 4.2. The map of the study area (indicated by the black polygon) with the seismic line that were selected for the key profiles.

4.1 Observation on Key Profiles

4.1.1 Profile 1

Profile 1 covers a distance of 74 km in the Vestbakken Volcanic Province in an E-W direction (Figure4.2). The glaciomarine sediments are divided into the three glaciomarine units GI, GII and GIII (Figures 4.3, 4.4).

The GI glaciomarine unit is divided into two megasequences, MS7-1 and MS7-3. The MS7 is a wedge- shaped megasequence, truncated by the URU (R1) towards the east and pinching out towards the west. MS6 is following the R6 morphology and is characterized by constant thickness. In general, the GI glaciomarine unit is characterized by a wedge-shape that is truncated by the URU and in the central part of the Profile 1. The GI is prograding westwards, and from the eastern part of the section towards the central part the unit is thickening.

The GII glaciomarine unit is divided into four megasequences, MS5 to MS2.MS5 is a wedge-shaped megasequence, pinching out towards the east. Its upper boundary cannot be traced towards the eastern part of the seismic section. MS4 is truncated by the URU (R1), towards the west it becomes thicker and is the thickest megasequence within GII unit (~ 850 ms in the western part of this seismic section). In general, the GII glaciomarine unit is pinching out towards the east.

The GIII glaciomarine unit consists of the MS1megasequence.The GIII unit is characterized by aggradational stacking pattern towards the east and by prograding stacking pattern towards the west.

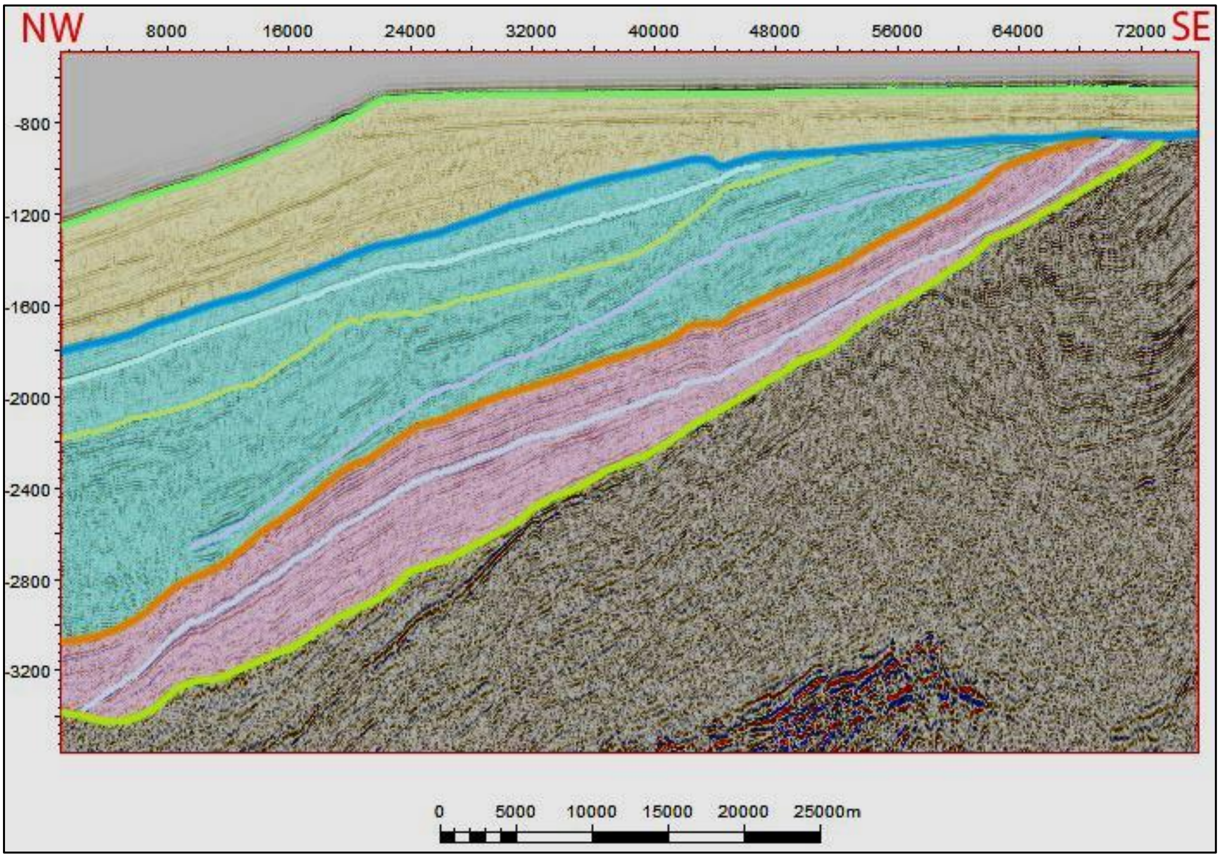

Figure 4.3. The profile 1 with the three glaciomarine units highlighted. For location see Figure 4.2.

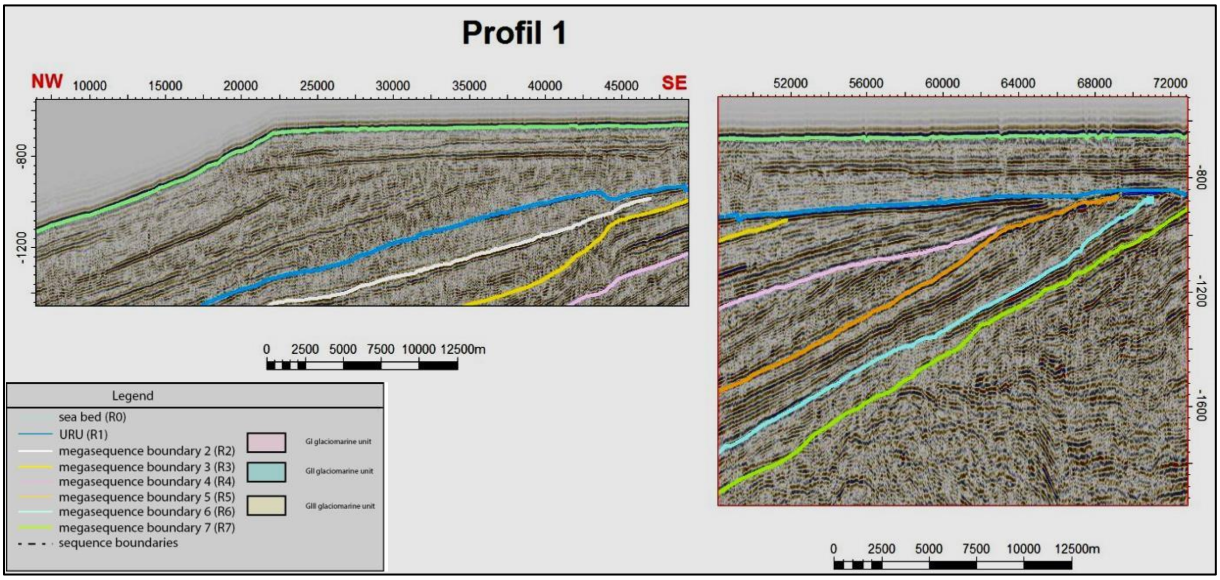

Figure 4.4. Detailed pictures of the key profile 1.

4.1.2 Profile 2

Profile 2 covers a distance of 76 km in the south of Vestbakken Volcanic Province and in the Bjørnøya Basin in a WNW-ESE direction (Figures 4.2, 4.5, 4.6). The GI glaciomarine unitis divided into two megasequences and is truncated by the URU (R1). The GII glaciomarine unit pinches out towards the east and is divided into four megasequences, MS5 to MS2. The MS4 megasequence thins towards the east and is abruptly thickening towards the west, from ~ 100 ms in the eastern and central part of the section to ~700 ms in the western part. It is characterized by transparent structureless reflection configuration pattern. The GIII glaciomarine unit is characterized by aggradational stacking pattern towards the east and progradational stacking pattern towards the west.

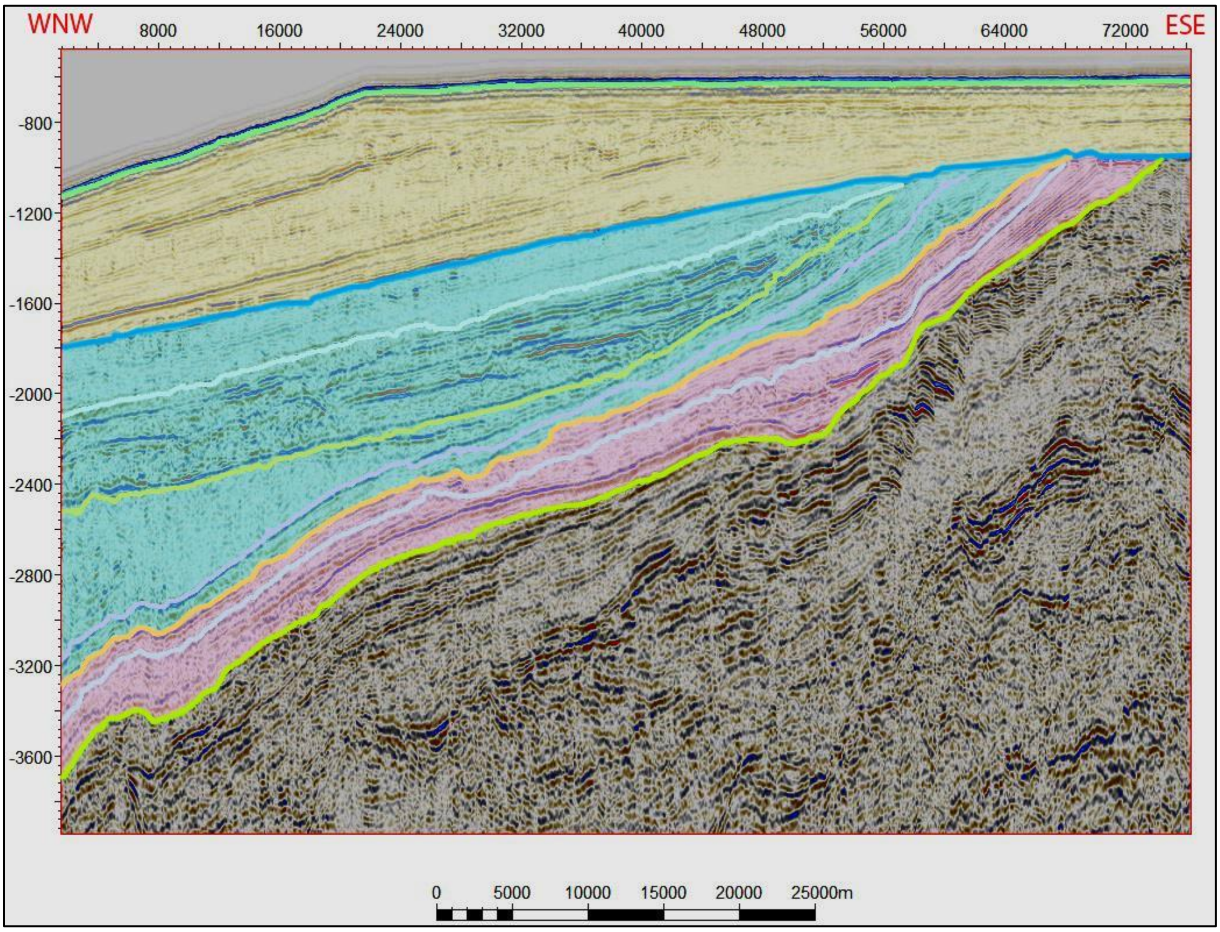

Figure 4.5. The profile 2 with the three glaciomarine units highlighted. For location see Figure 2.

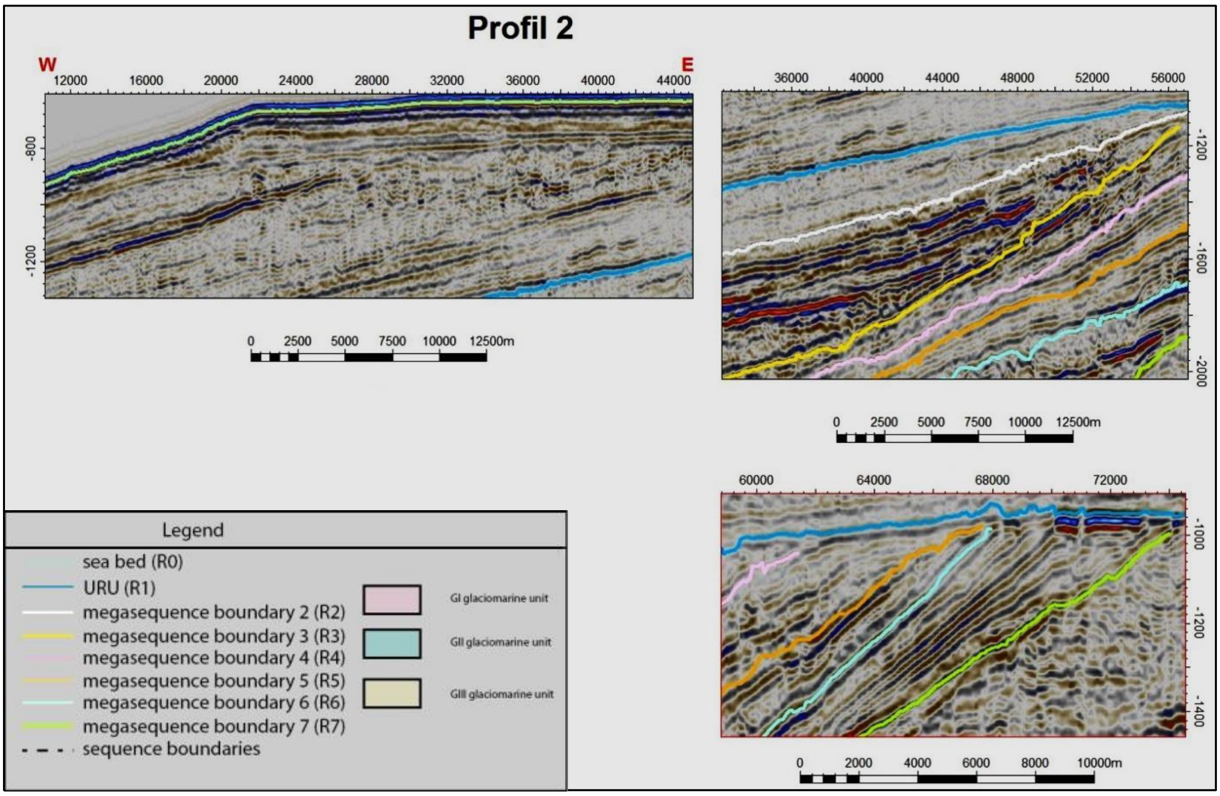

Figure 4.6. Detailed pictures of the key profile 2.

4.1.3 Profile 3

Profile 3 covers a distance of 63 km in the northern part of the Sørvestsnaget Basin in a SW-NE direction(Figures 4.2, 4.7, 4.8). The GI glaciomarine unit is divided into two megasequences, MS7 and MS6. It is a wedge-shaped megasequence that is truncated by the URU (R1). Its thickest part is observed in the central part of the section (~ 32 km in the horizontal axis of the section) and its maximum time-thickness is ~ 500 ms. The uppermost boundary of the GI unit, the R5, has partly preserved the offlap breaks but they are incised by erosional channels. The GII glaciomarine unit pinches out towards the east and is divided into four megasequences, MS5 to MS2.All of these megasequences are truncated by the URU (R1). The GIII glaciomarine unit is equivalent to MS1 megasequence. It is characterized by aggradational stacking pattern towards the east and progradational stacking pattern towards the west.

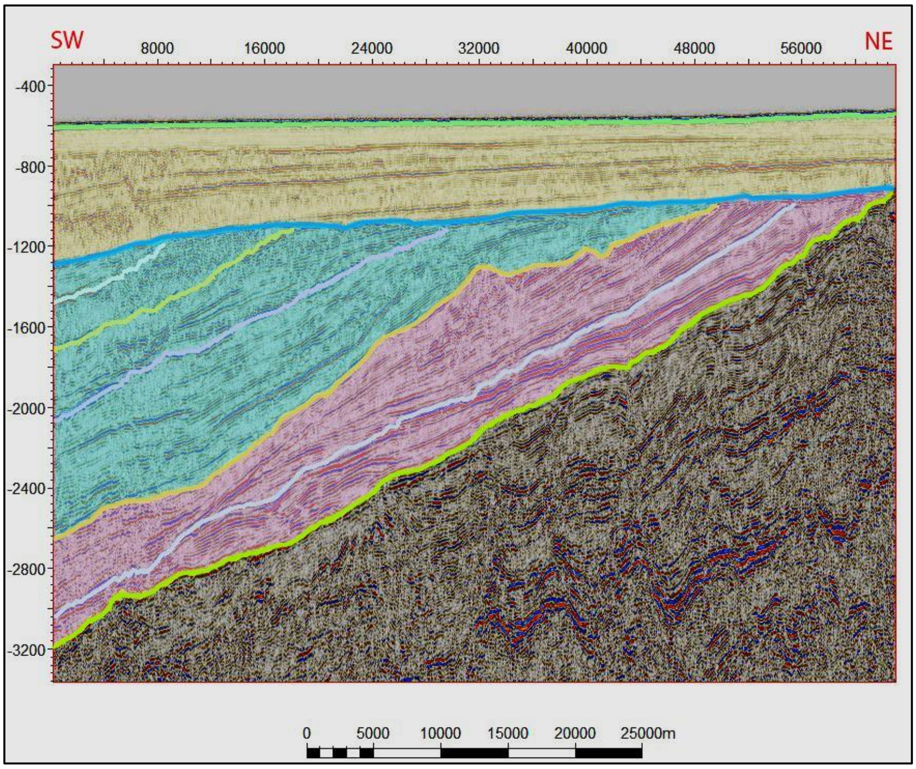

Figure 4.7. The profile 3 with the three glaciomarine units highlighted. For location see Figure 2.

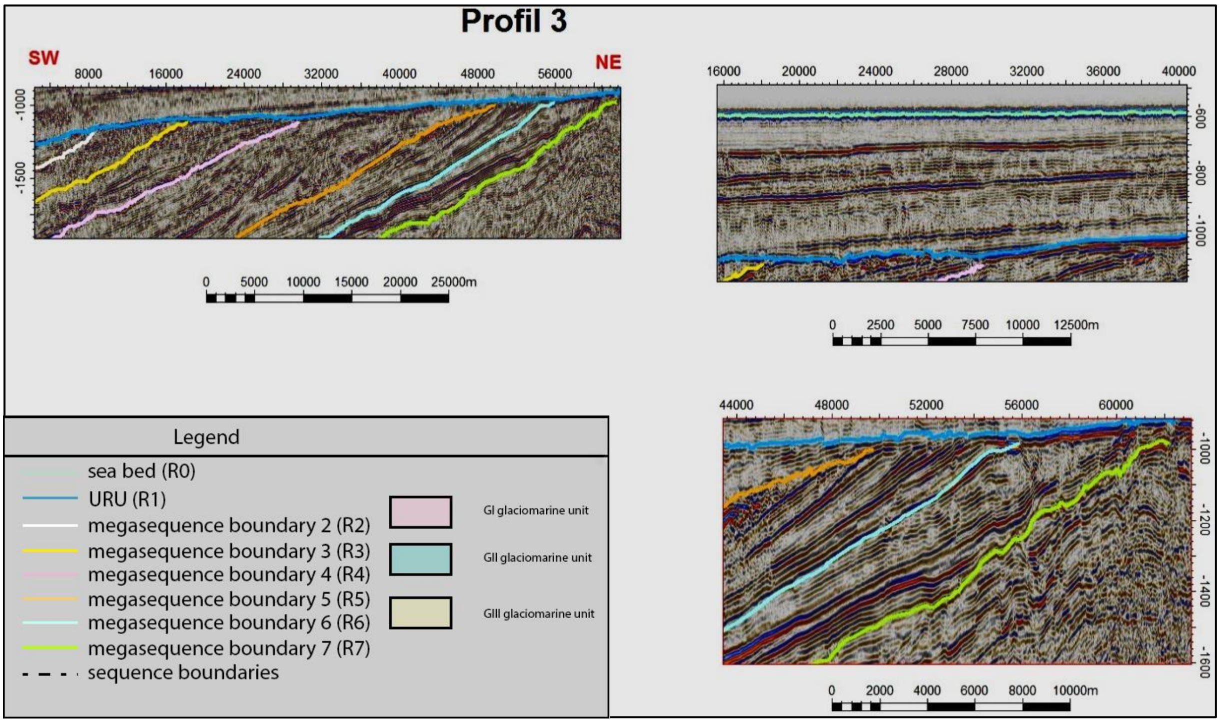

Figure 4.8. Detailed pictures of the key profile 3.

4.1.4 Profile 4

Profile 4 covers a distance of 80 km in the south of the Velsemøy High in a SW- NE direction (Figures 4.2, 4.9, 4-10). The GI glaciomarine unit is divided into two megasequences, MS7 and MS6. The GI unit is a wedge-shaped unit with its thickest part in the center of the section (in horizontal distance ~28- 48 km) to be ~600 m. MS7 is truncated by R5 sequence boundary, and the MS6 megasequence is pinching out towards the west, and in the western part its maximum time-thickness is ~ 1000 ms. The GII glaciomarine unit pinches out towards the east and is divided into four megasequences, MS5 to MS2.Within the GII glaciomarine unit the offlap breaks are well preserved. The megasequences are characterized by aggradational stacking pattern towards the west. The GIII glaciomarine unit consists of the MS1 megasequence. It is characterized by aggradational stacking pattern towards the east and progradational stacking pattern towards the west.

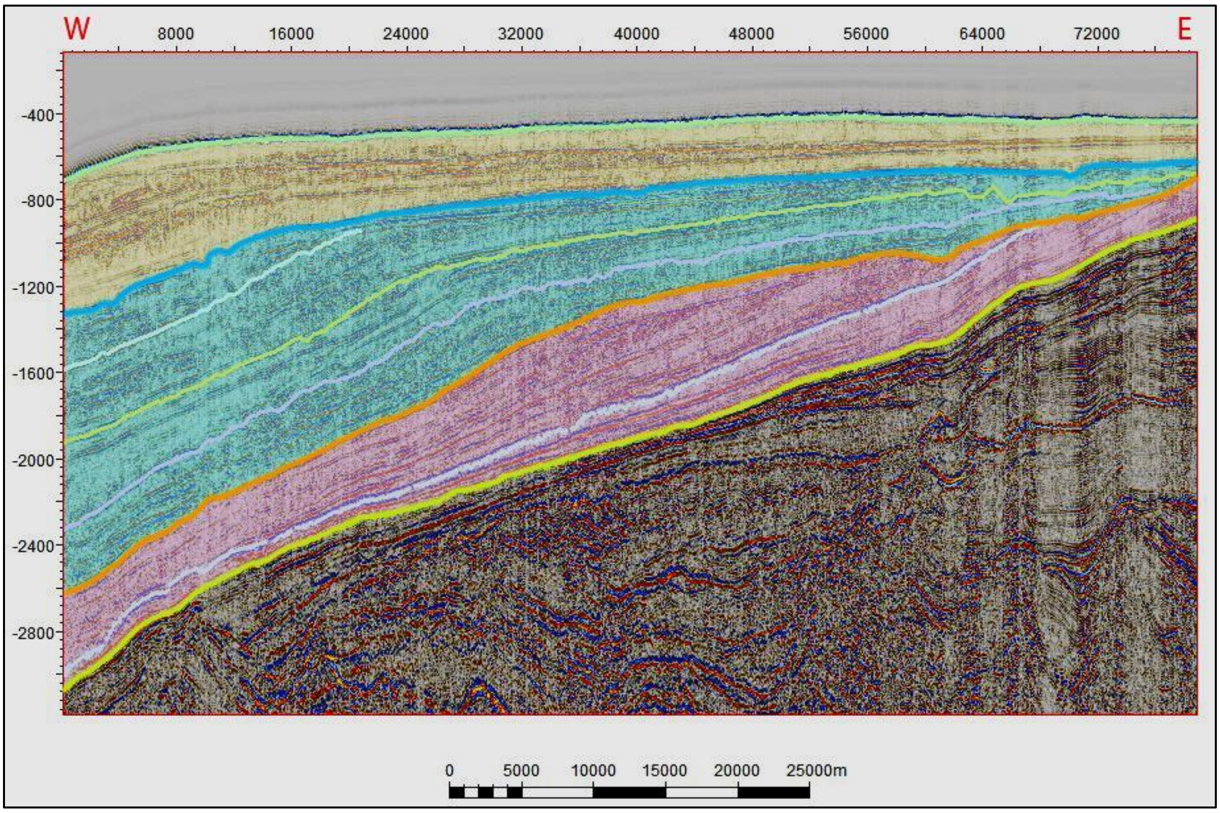

Figure 4.9. The profile 4 with the three glaciomarine units highlighted. For location see Figure 2.

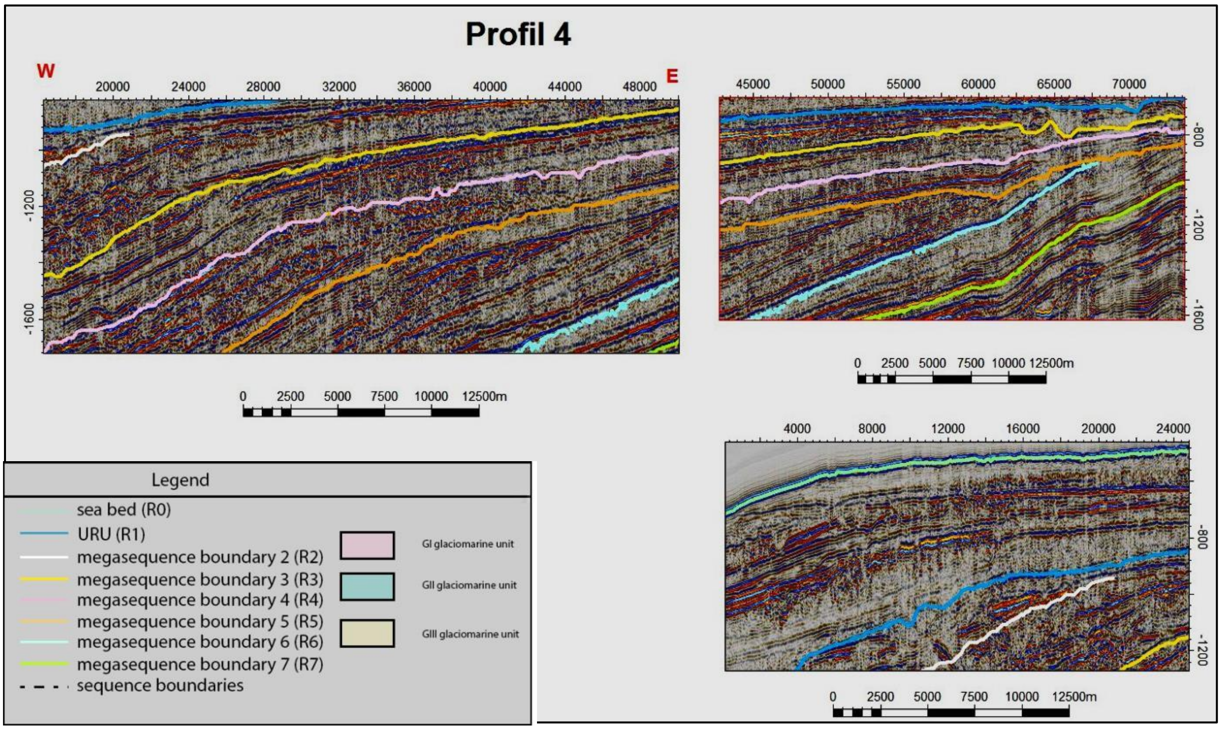

Figure 4.10.Detailed pictures of the key profile 4.

4.1.5 Profile 5

This profile covers a distance of 115 km from the Vestbakken Volcanic Province in the North to the Sørvestsnaget Basin in the South in a NNE- SSW direction (Figures 4.2, 4.11, 4.12). The GI glaciomarine unit is divided into two megasequences, MS7 and MS6. The GI glaciomarine unit is characterized by oblique tangential reflection configuration and is thinning towards the NNE (from~ 450 ms in the NNE part to 250 ms). The GII glaciomarine unit pinches out towards the NNE and is divided into four megasequences, MS5, MS4, MS3 and MS2. MS5 is characterized by erosional channels that are incising the internal reflectors of the megasequence and also the boundary at its top (R4). The GIII glaciomarine unit consists of the MS1 megasequence. It is characterized by aggradational stacking pattern.

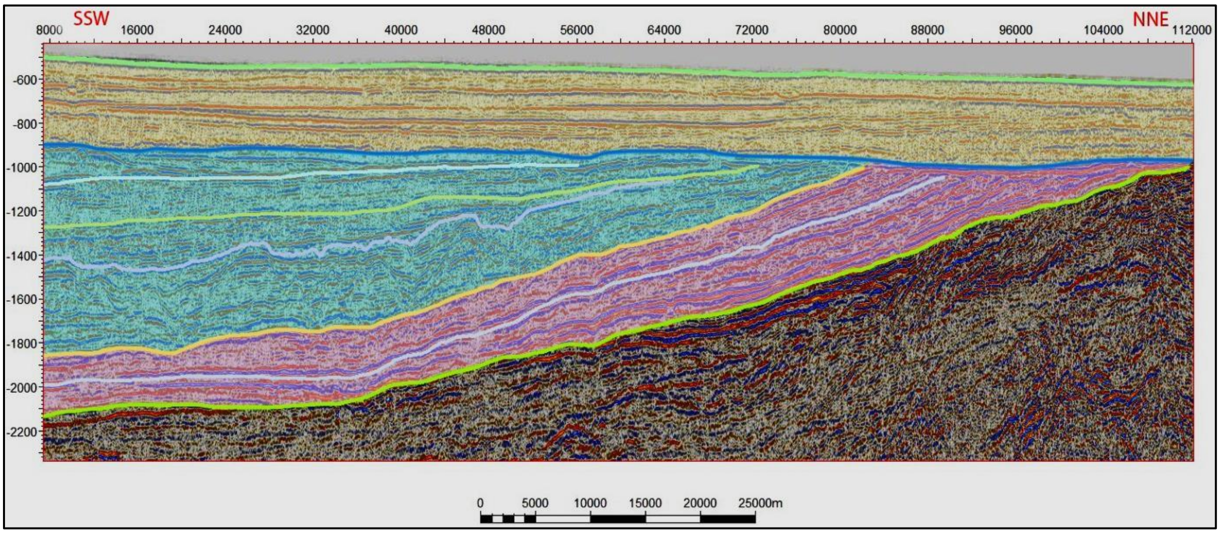

Figure 4.11.The profile 5 with the three glaciomarine units highlighted. For location see Figure 2.

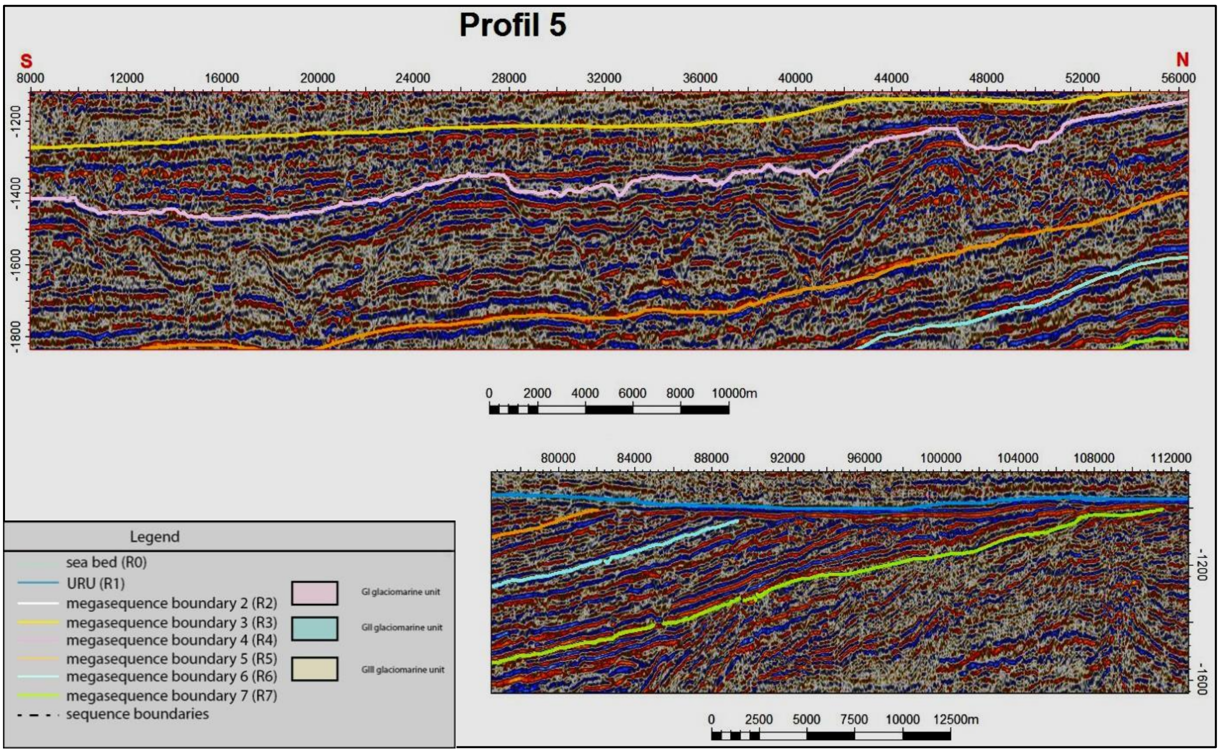

Figure 4.12.Detailed pictures of the key profile 5.

4.2 Observations on the seismic megasequences and sequences

In this subchapter a sequence analysis of the seven megasequences and their sequences will be presented. The analysis will be done from the GI towards the GIII glaciomarine unit. As already mentioned, the glaciomarine sediments are divided into three glaciomarine units (GI- GIII). These units are subdivided into 7 megasequences (in the literature referred as S1-S7). In this study the megasequences were subdivided into *sequences* (see Chapter 3). The glaciomarine units and the megasequences are mappable in the whole study area. The identified sequences within each megasequence are not all represented in every seismic section. For this reason, it has not been possible to correlate the sequences through the study area. In the following, seismic sections where the maximum number of sequences was observed are presented. In Figure 4.13, the maximum number of sequence boundaries and sequences for each megasequence is presented. In addition to that, a number of characteristic features within the megasequences will also be presented. The generated time-thickness maps were an additional useful tool to identify the areas with the maximum number of sequences within the megasequences (Figure4.14). In the thickest part of each megasequence, the number of the identified sequences was higher.

		Sequence Boundaries	Sequences
GIII	MS1	5	6
GII	MS2	1	4
	MS3	2	4
	MS4	2	3
	MS5	3	3
GI	MS6	3	2
	MS7	6	7

Figure 4.13. In the table the maximum number of sequences that were identified in each megasequence.

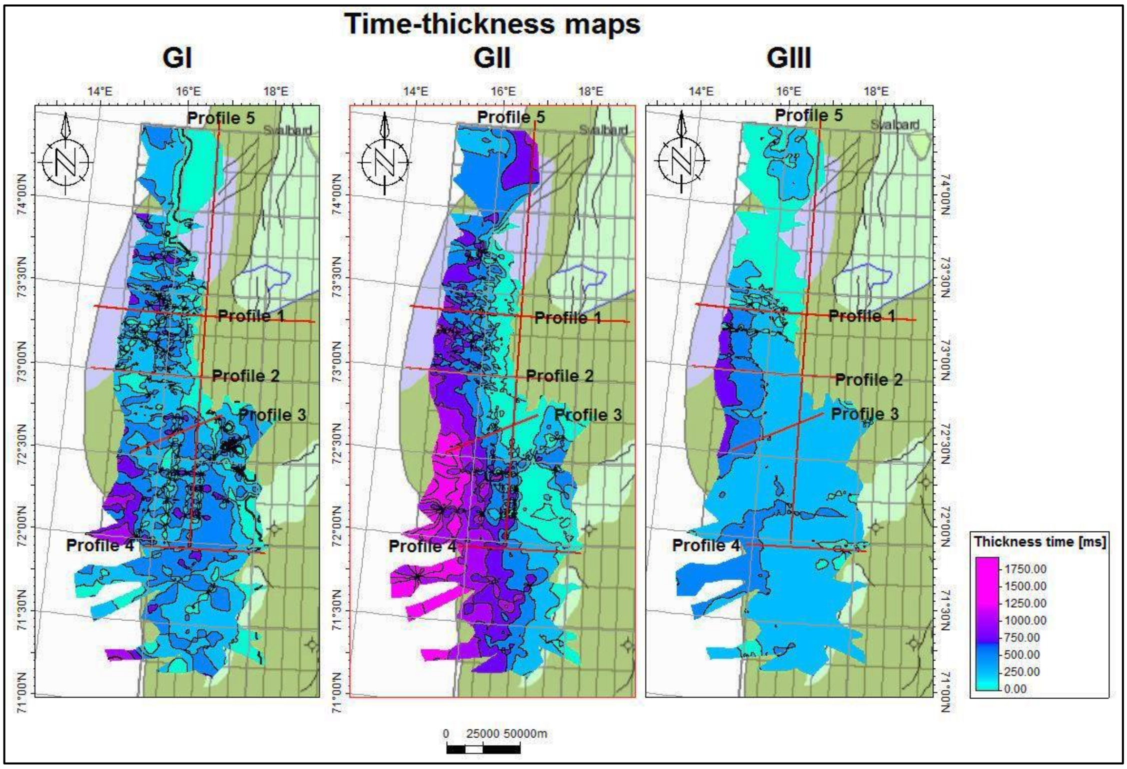

Figure 4.14. Time- thickness maps for each glaciomarine unit.

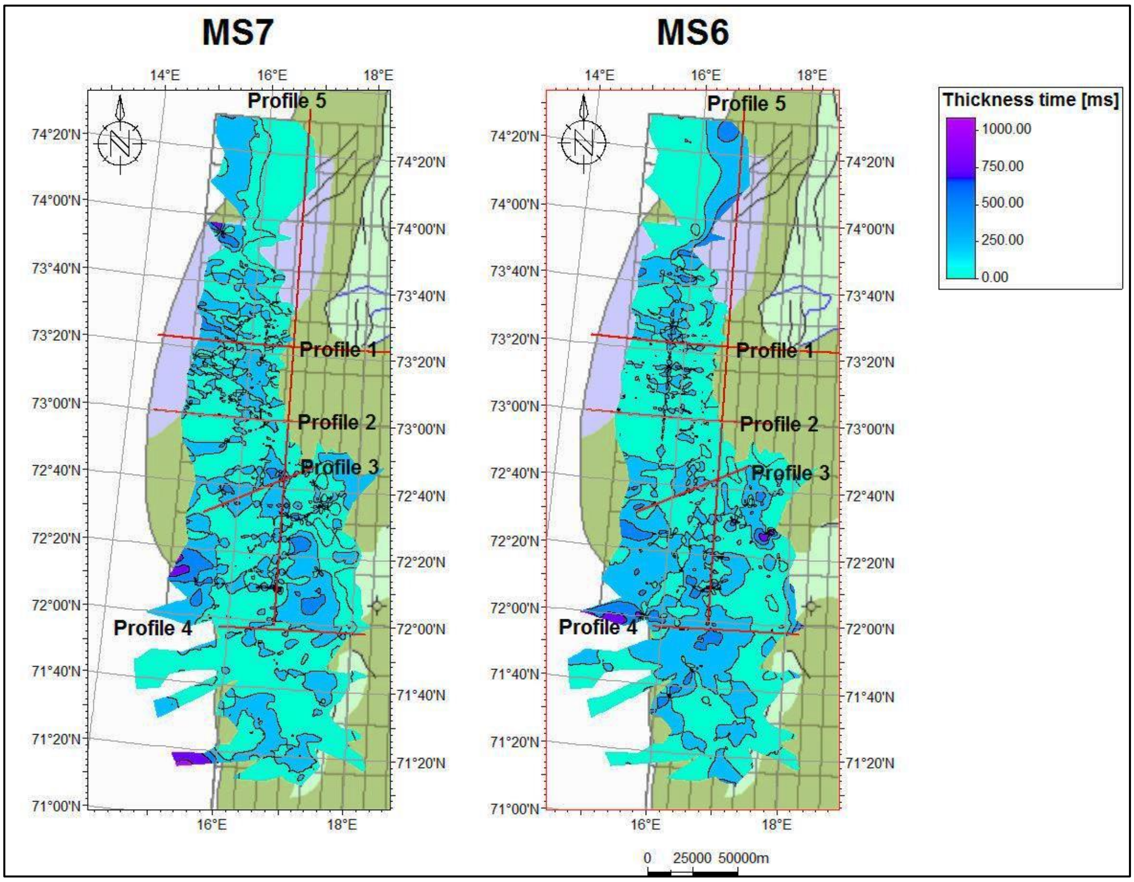

Figure 4.15.Time- thickness map for the megasequences of the GI glaciomarine unit. Contour interval 250 m.

4.2.1 Seismic sequence analysis

4.2.1.1 GI glaciomarine unit (megasequence 1- megasequence 10)

In Figure 4.15, time-thickness maps for MS7 and MS6 megasequences are presented, respectively. Its maximum time-thickness is ~ 1300 ms in the western part of the Bjørnøya Fan, restricted to the area between 72°30'N to 71°80'N.

4.2.1.1.1 Megasequence 7

The maximum number of identified sequences in this megasequence is six (Figure4.16). They represent together the lower part of the glaciomarine sediments in the study area. In general, the reflections are parallel to subparallel, dipping westwards and being truncated by R1 (URU).

Mainly, the clinoforms are characterized by tangential oblique progradational pattern. In general, the sequences in megasequenceMS7 are not characterized by erosional channels. But in some cases channels can be observed (Figure 4.17).

4.2.1.1.2Megasequence 6

The maximum number of identified sequences in megasequence 6 is four (Figure 4.18). The internal reflection configuration of the sequences is parallel to subparallel, dipping westward sand being truncated by the R1 sequence boundary (Figure 4.9- 4.10).

Locally, the sequences can be characterized by oblique to sigmoid progradational configuration (Figure 29). Erosional channels have also been observed within MS6 (Figure 30).

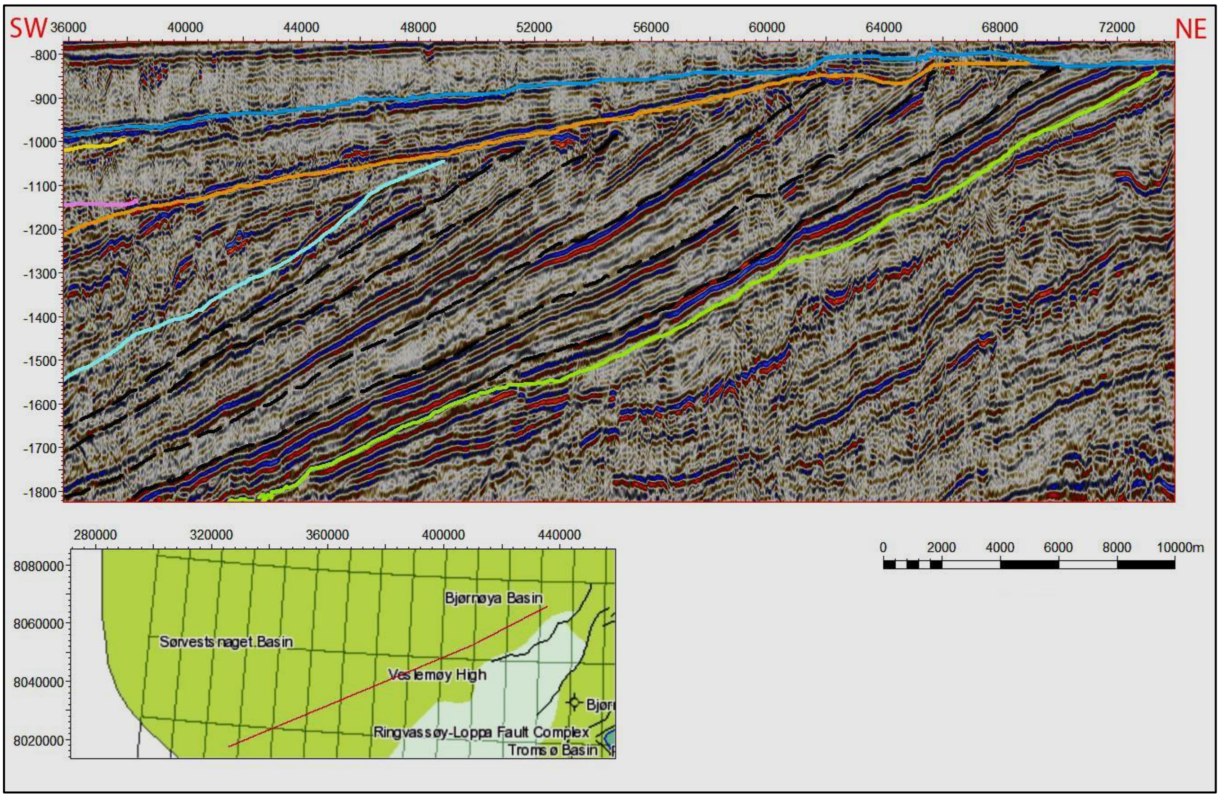

Figure 4.16. Maximum number of identifies sequences within the MS7 (marked with dashed black line).

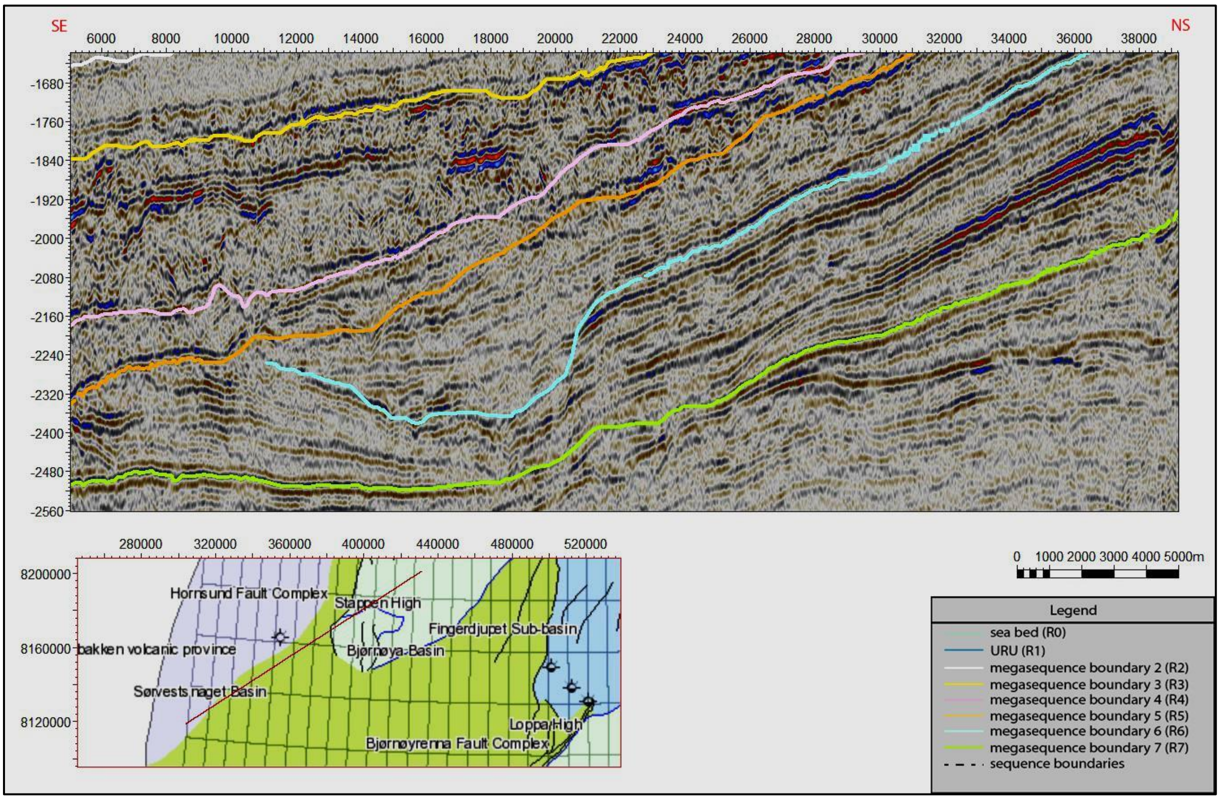

Figure4.17. Erosional channels within MS7 and MS6 megasequences.

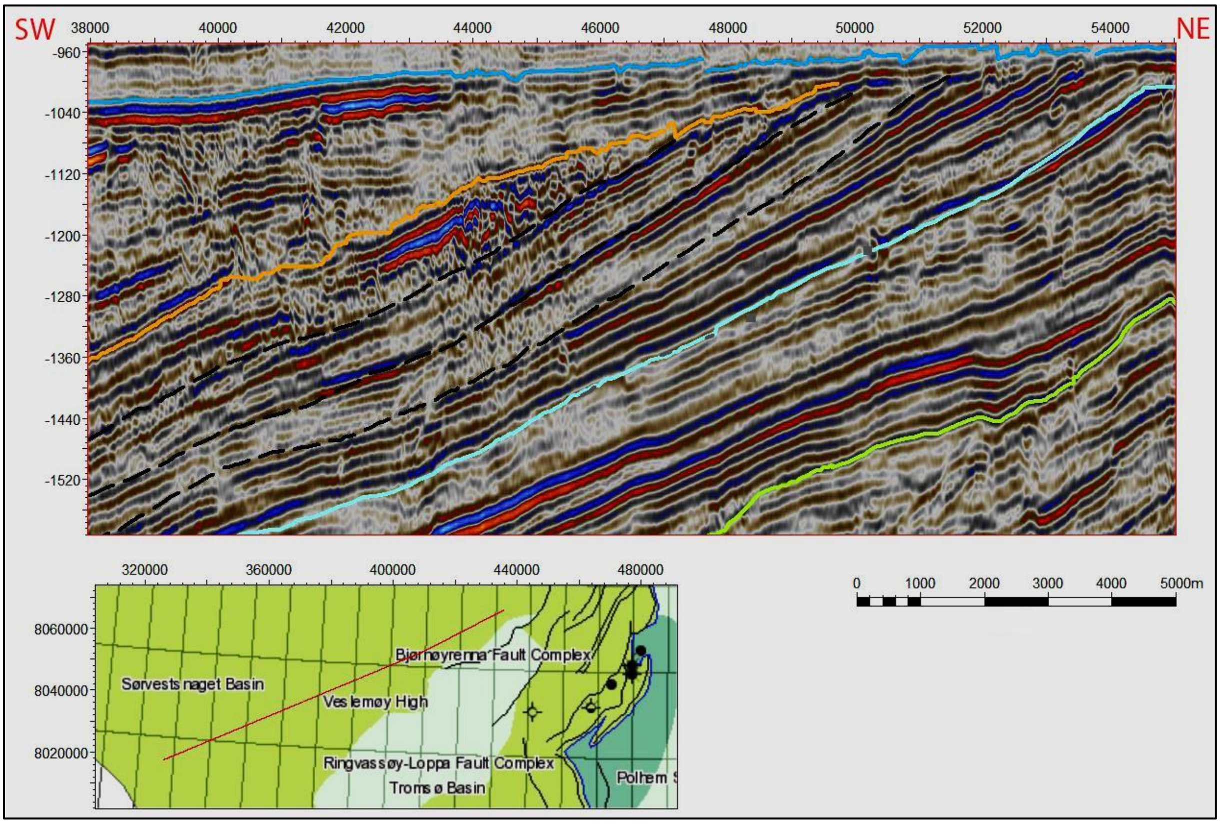

Figure 4.18. Maximum number of identifies sequences within the MS6 (marked with dashed black line).

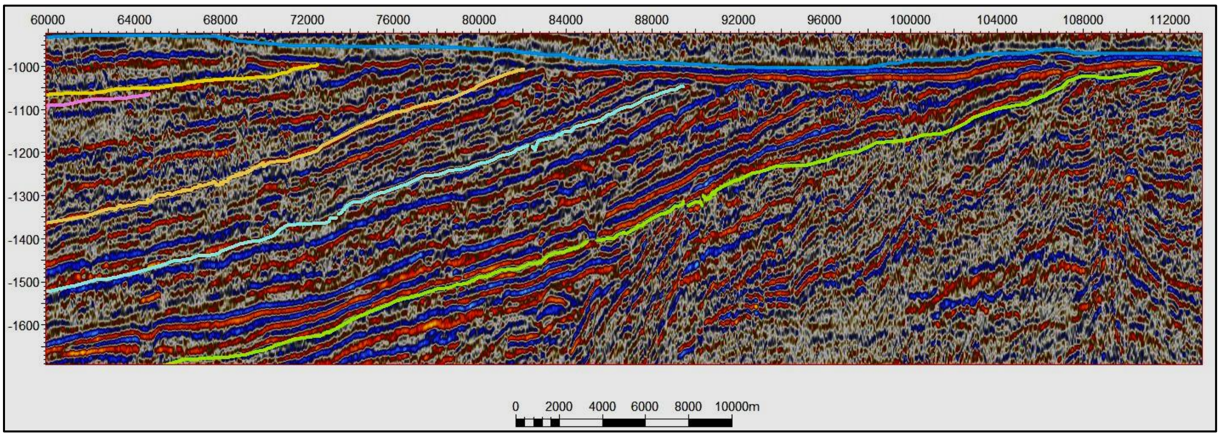

Figure 4.19. 1645-86 (key profile 5) MS6 and MS7 are truncated by R1 (URU). Both are characterized by tangential reflection configuration pattern.

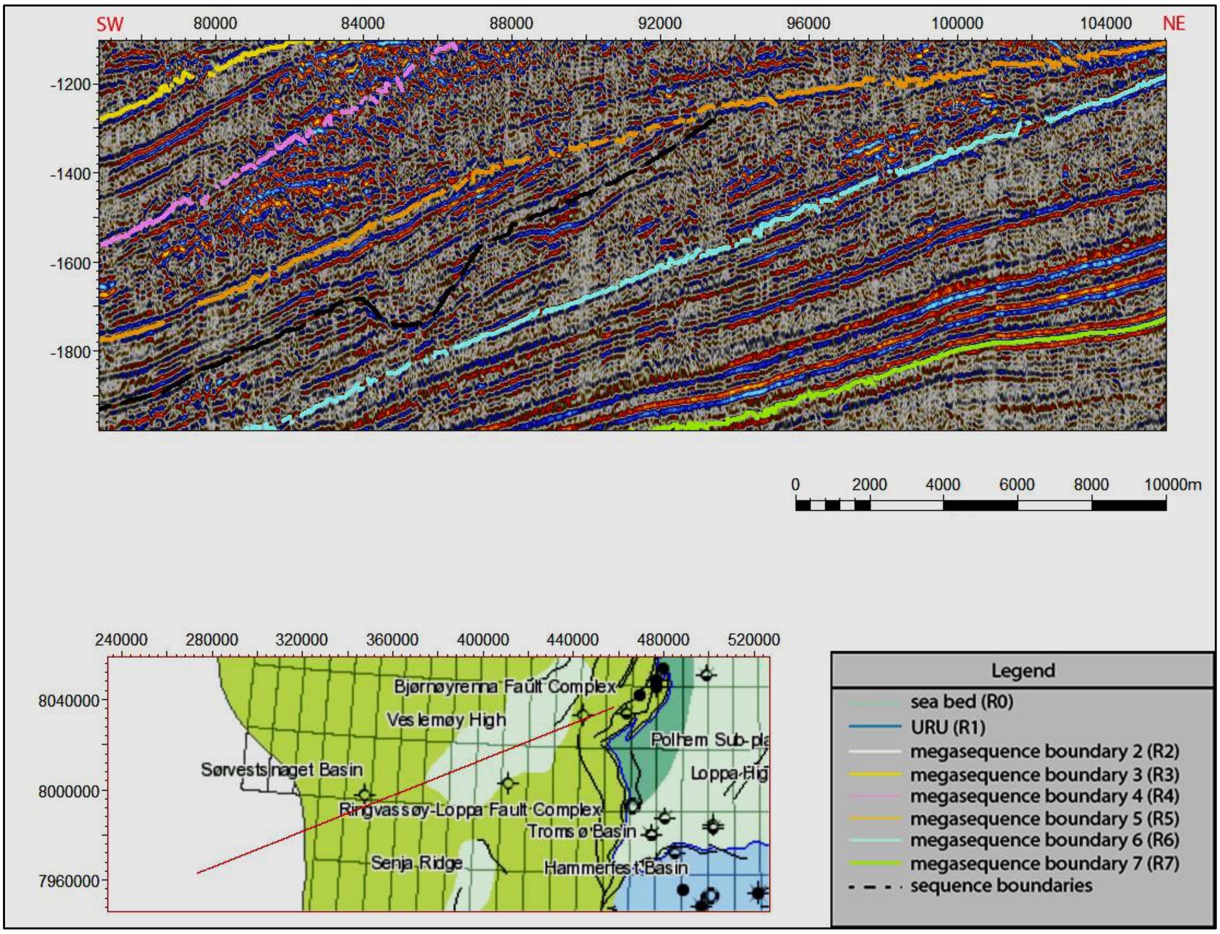

Figure 4.20.Erosional channels within MS6 megasequences.

4.2.1.2 GII glaciomarine unit (megasequence 11- megasequence 22)

From the R5 sequence boundary and upwards a change in pattern of reflectors can be observed. Erosional channels and slides have affected the sequences in the GII glaciomarine unit. The time-thickness maps for GII glaciomarine units are presented in Figure 4.21. Its maximum time-thickness is ~ 1800 ms in the western part of the Bjørnøya Fan, restricted in the area between 72°45’N to 71°25’N.

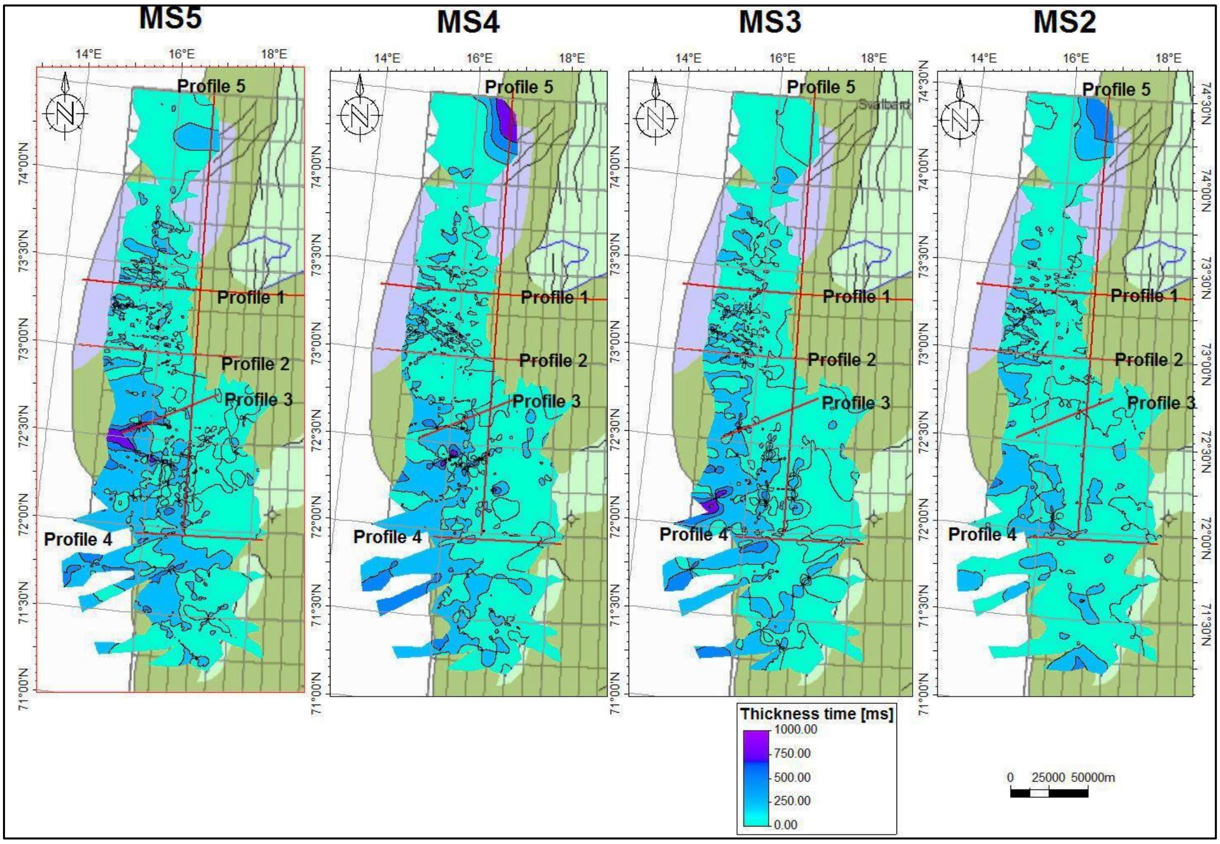

Figure 4.21.Time- thickness map for the megasequences of the GII glaciomarine unit. Contour interval 250 m.

4.2.1.2.1Megasequence 5

The maximum number of identified sequences within the megasequence MS 5 is four (Figures 4.22, 4.23). In general, the reflectors are dipping westwards. The seismic sequences are characterized by sigmoid, progradational reflection configuration (Figure4.22) or in some cases by a complex sigmoid-oblique progradational reflection configuration. In some of the seismic sections the sequences are characterized by subparallel reflection configuration (Figure 4.23). The reflectors are truncated by the R4 or R1 sequence boundaries. The uppermost boundary of the megasequenceMS5 is determined by toplaps that in many cases are within seismic resolution. As mentioned previously above, erosional channels can be observed along the R5 seismic boundary and upwards, something that were not observed in the megasequences within the GI glaciomarine unit (Figure 4.24).

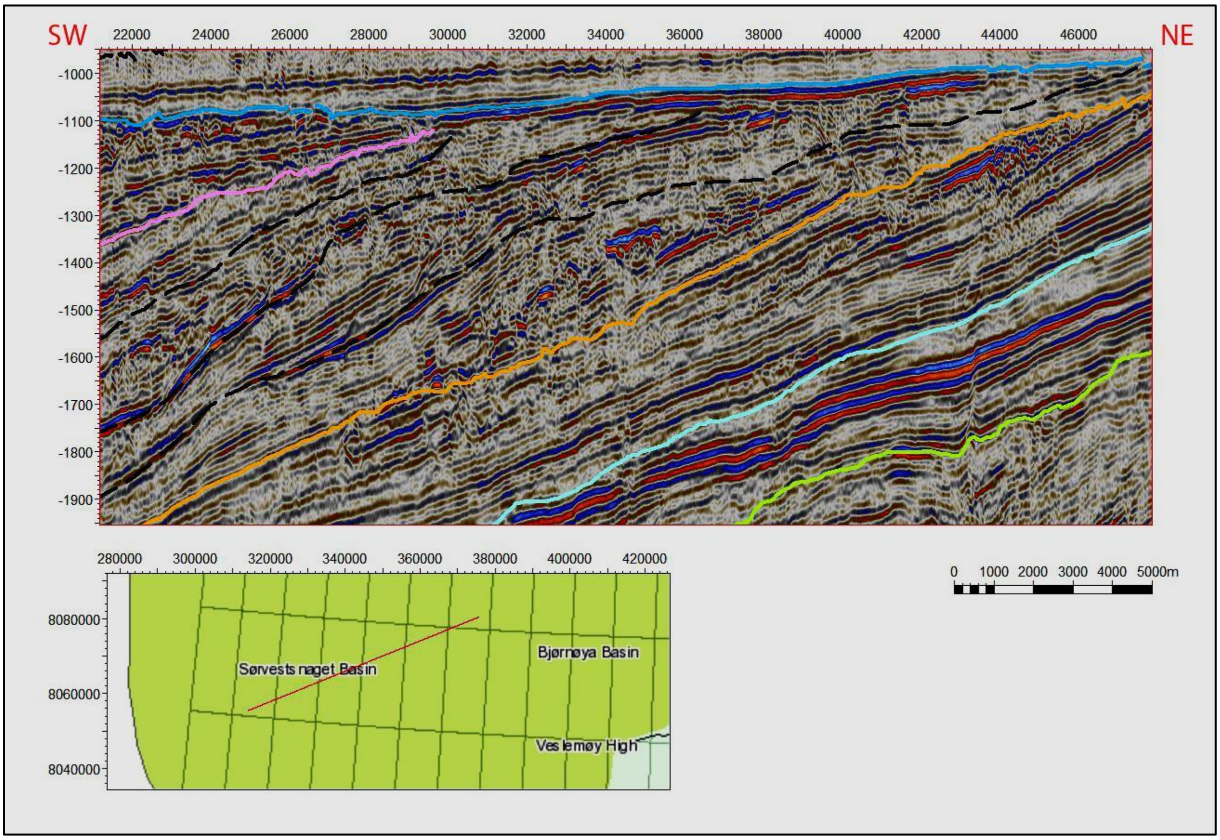

Figure 4.22. Maximum number of identifies sequences within the MS5 (marked with dashed black line).

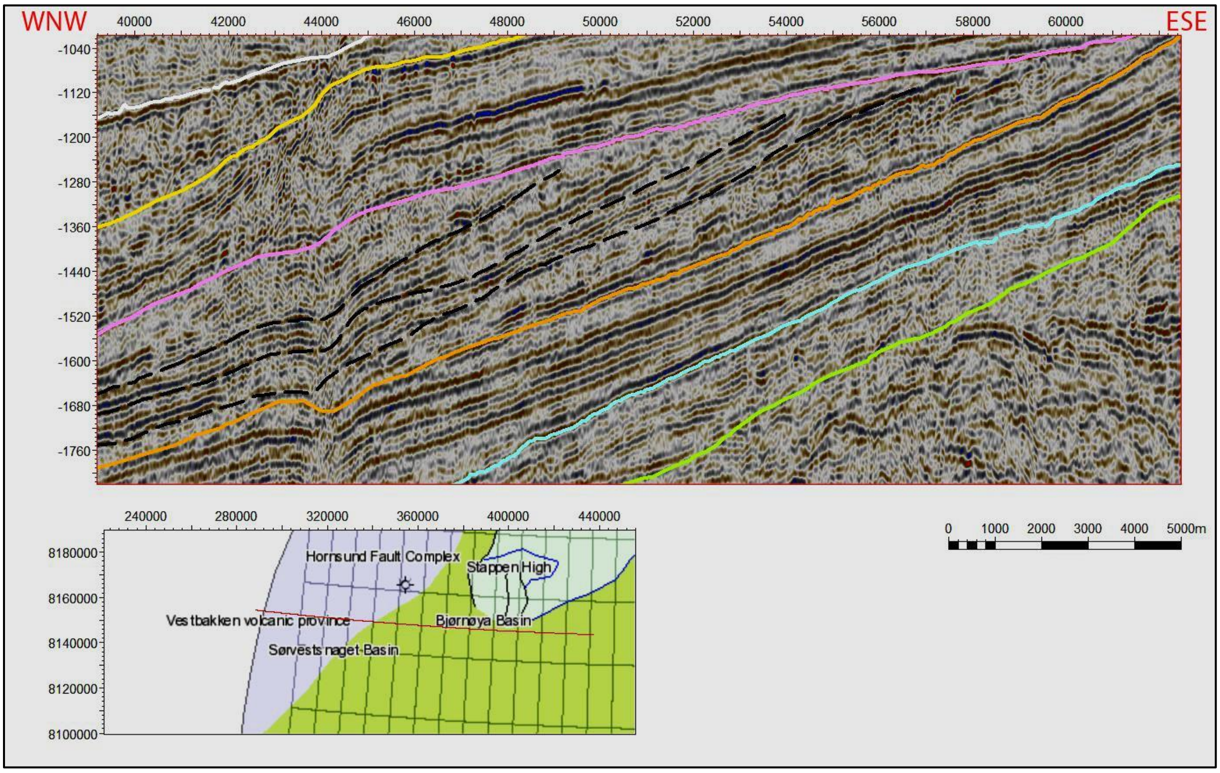

Figure 4.23.Maximum number of identifies sequences within the MS4 (marked with dashed black line).

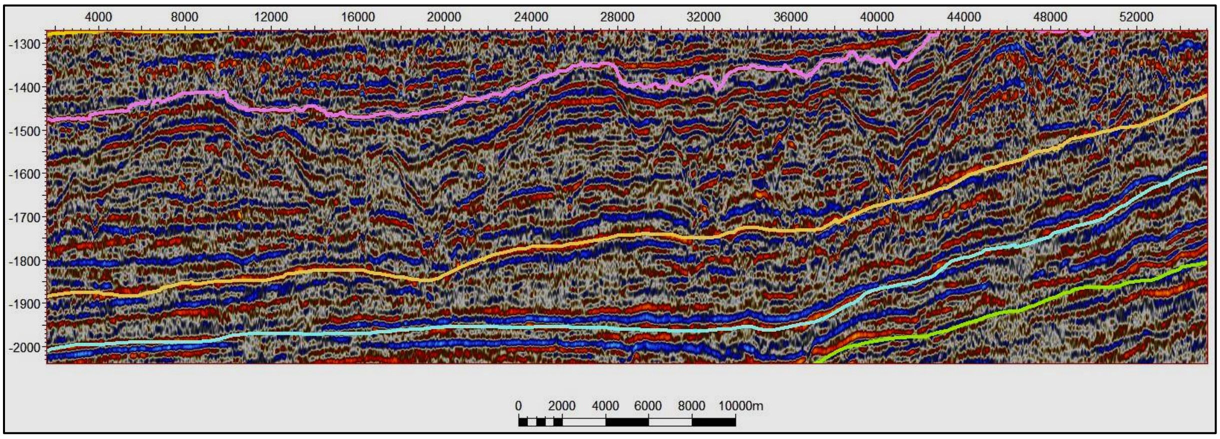

Figure 4.24Key profile 5. Erosional channels within the MS5.

4.2.1.2.2 Megasequence 4

The maximum number of identified sequences in megasequence 4 is three (Figure 4.25).They are all truncated by the R1 (URU). The megasequence is characterized by subparallel to wavy reflection configuration. The upper boundary of the megasequence is indicated by toplap that in many cases is within the seismic resolution. The reflectors are truncated by R3 or R1 sequence boundaries.

4.2.1.2.3Megasequence 3

The maximum number of identified sequences in this megasequence is three (Figure 4.26). The megasequence 3 is characterized by subparallel to wavy reflection configuration dipping westwards. The reflectors are truncated by R2 or R1 sequence boundary. Their upper boundaries are indicated by toplap.

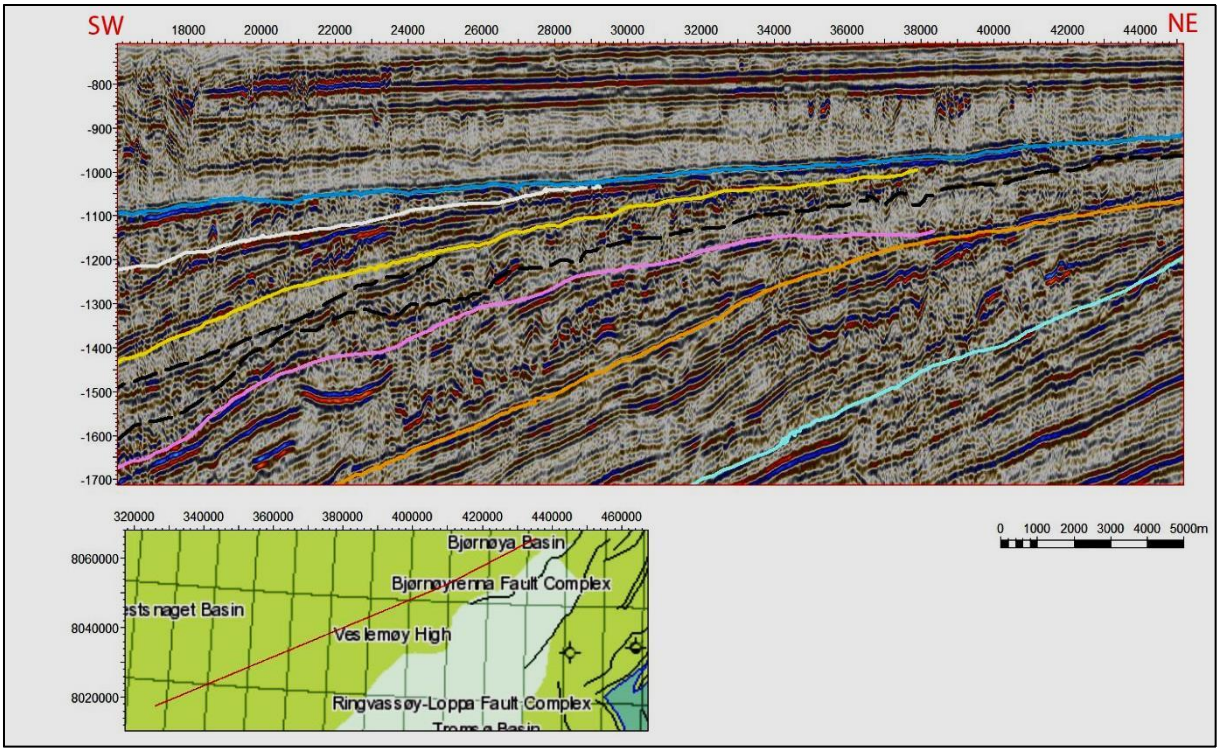

Figure 4.25 Maximum number of identifies sequences within the MS4 (marked with dashed black line).

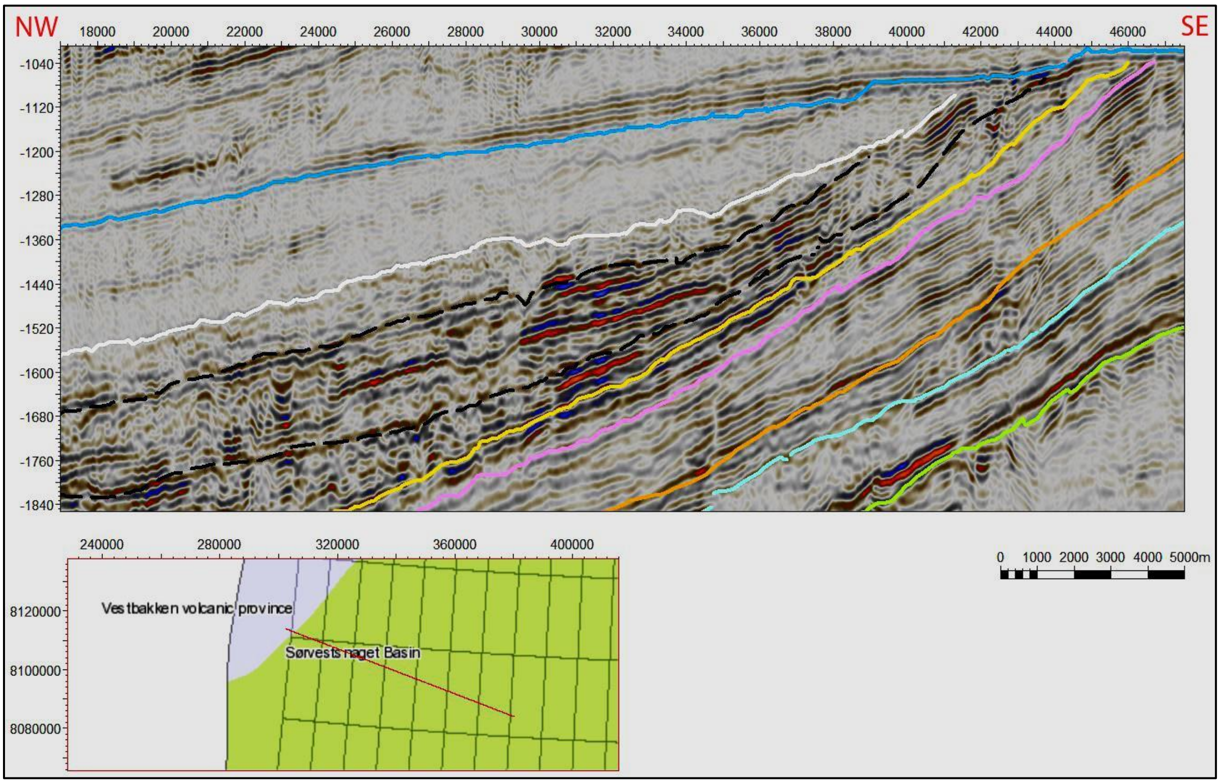

Figure4.26 Maximum number of identifies sequences within the MS3 (marked with dashed black line).

4.2.1.2.3Megasequence 2

The maximum number that was observed in the MS2 is two (Figure 4.27). In general, the megasequence is characterized by transparent reflectors. The reflection configuration can also vary from subparallel, wavy to chaotic. In many seismic sections megasequence 2 is characterized by a structureless or transparent reflection pattern. The upper boundaries are indicated by toplap, and the reflectors are truncated by the R1 (URU)(Figure 4.28).

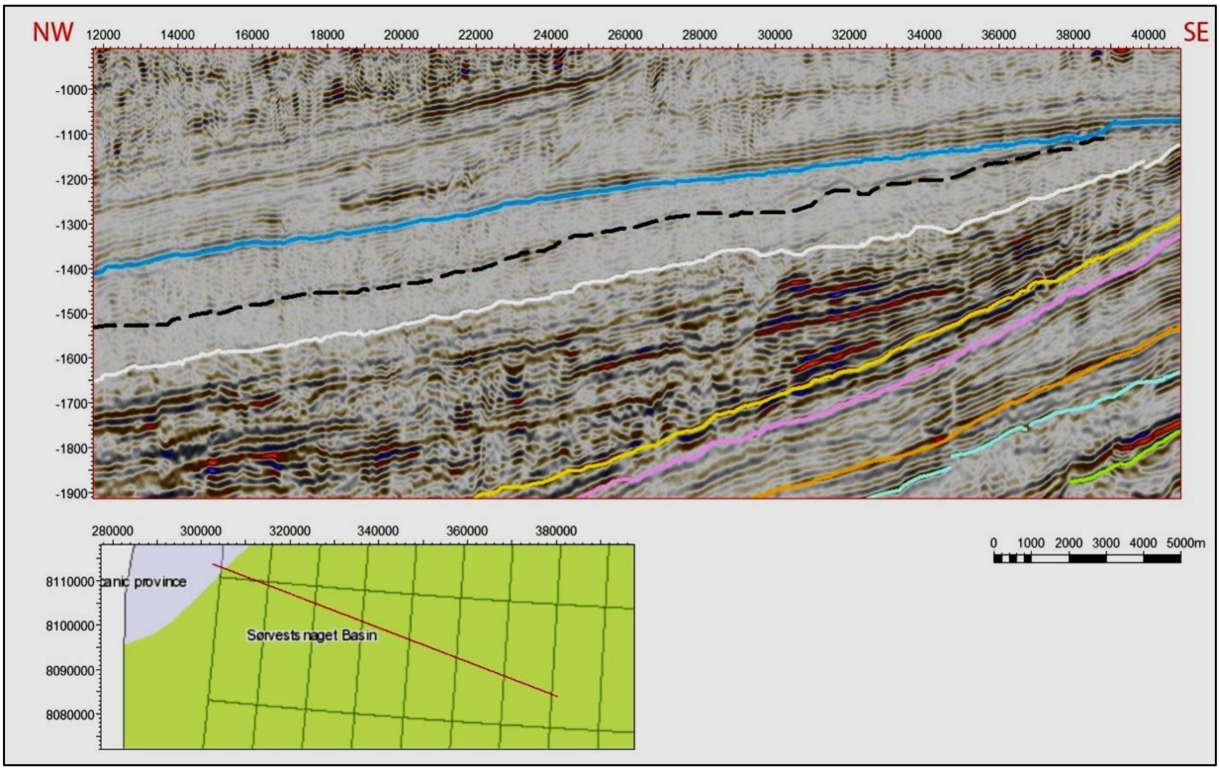

Figure 4.27.Maximum number of identifies sequenced within the MS2 (marked with dashed black line).

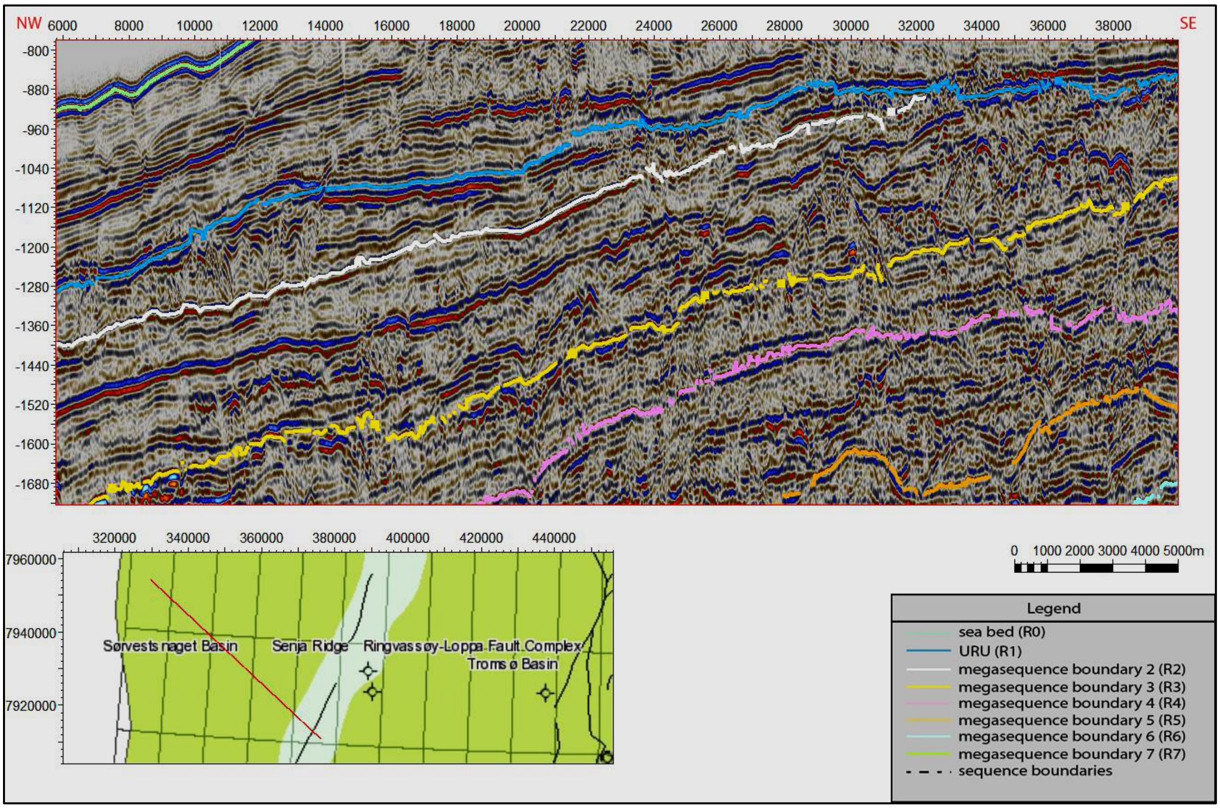

Figure 4.28.The MS2 megasequence is truncated by the URU (R1).

4.2.1.3GIII glaciomarine unit (megasequence 23- megasequence 28)

In most profiles the GIII is characterized by aggradational stacking pattern. Locally, it is characterized by weak progradating stacking pattern. In that case it can be subdivided into several sequences, with the maximum number to be six (Figures 4.29, 4.30). Only in the part of the Bjørnøya Fan, where the thickest deposits of GIII glaciomarine unit are observed (see time-thickness maps of GIII unit, Figure4.14), six sequences have been identified. The glaciomarine unit GIII is equivalent to the megasequence 1 (MS1). The MS1 is the youngest megasequence in the Bjørnøya Fan, and it contains sediments deposited between R1(URU) and the sea bed (R0)(Figures4.29. 4.30).Its maximum time-thickness is ~ 1100 ms in the western part of the Bjørnøya Fan, restricted to the area between 73°15’N to 72°15’N.

In general, the MS1 megasequence contains reflectors that characterize sequences having aggradational stacking pattern (Figure4.31). In the outer parts of the Bjørnøya Fan, towards the deep sea basin where the thickest deposits of the GIII unit are located, the MS1 is characterized by a weak progradational pattern. In places where sediments in MS1 are not so thick and the sequence MS1 is characterized by parallel to subparallel reflection configuration (aggradational pattern), no further subdivision of MS1 can be achieved. Erosional channels can also be found in the MS1 (Figure 4.31). Also locally, packages with chaotic reflectors can be observed within the MS1 (Figure 4.32).

In general, the best preserved clinoforms can be observed in the outer parts of the Bjørnøya Fan, where the thickest deposits are observed (see time-thickness maps in Figure 4.14). Also In the area of the Vestbakken Volcanic Province the offlap breaks of seismic sequences are mainly preserved. In the seismic sections that are parallel to the main axis of the Bjørnøya Trough, erosional channels cannot be observed. In general, all megasequences, whenever they are not disturbed by slide or erosional channels towards the deep sea basin, their reflections tend to become subparallel to parallel (Figure 4.33).

Based on the subdivision of the megasequences into sequences, a relative chronology of the main sequence boundaries was made. The ages are presented in Figure 4.34 together with the ages of the same boundaries published in literature.

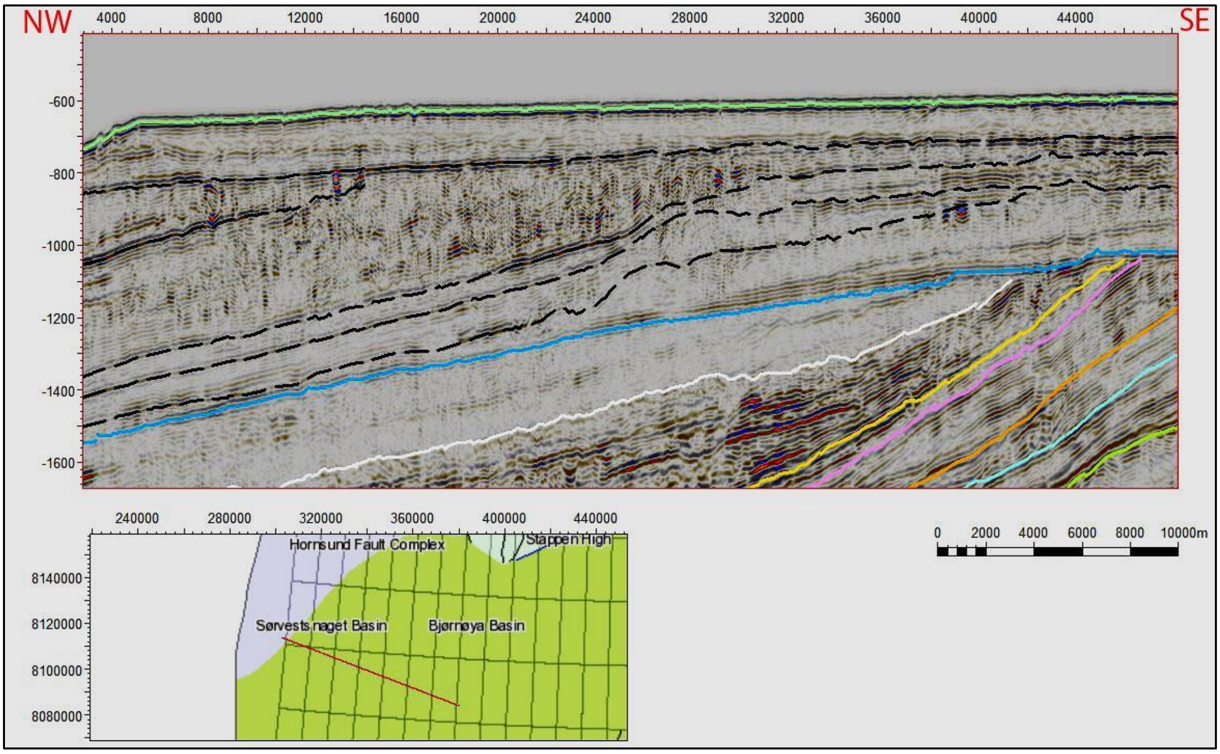

Figure 4.29. Maximum number of the identified sequences within the MS1 (marked with dashed black line).

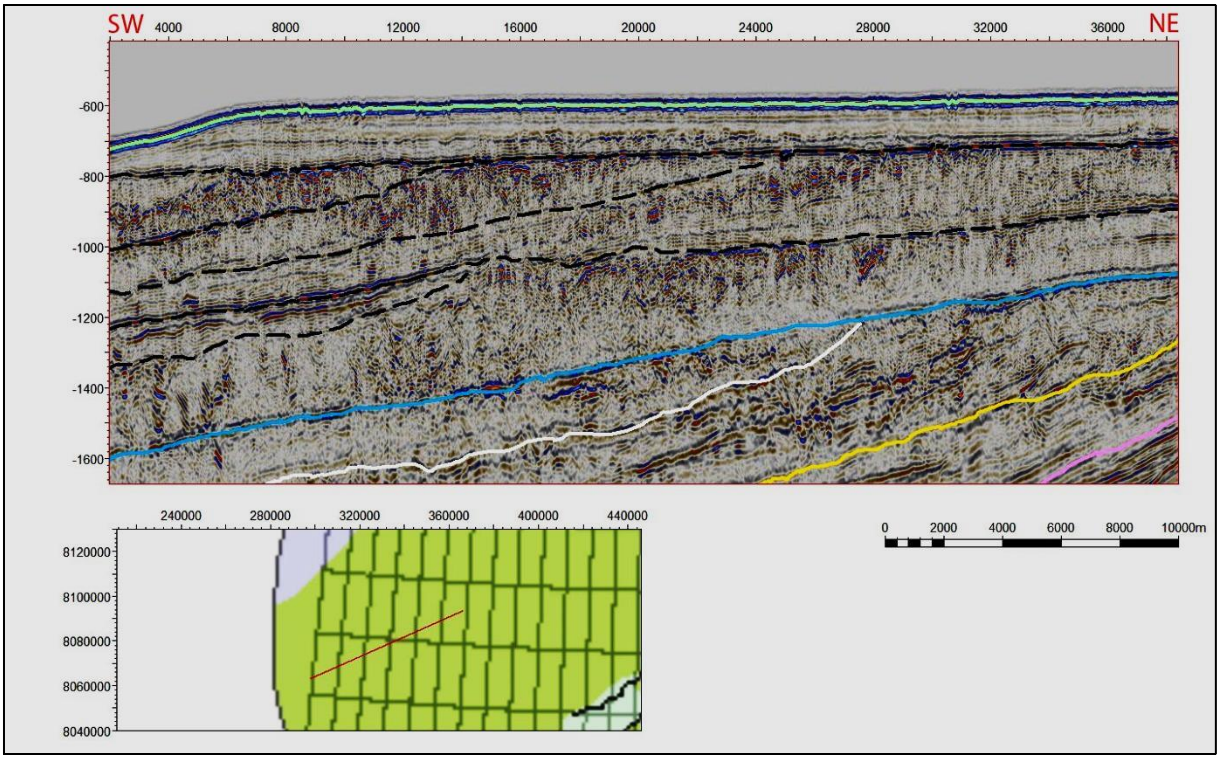

Figure4.30 Maximum number of identifies sequences within the MS1 (marked with dashed black line).

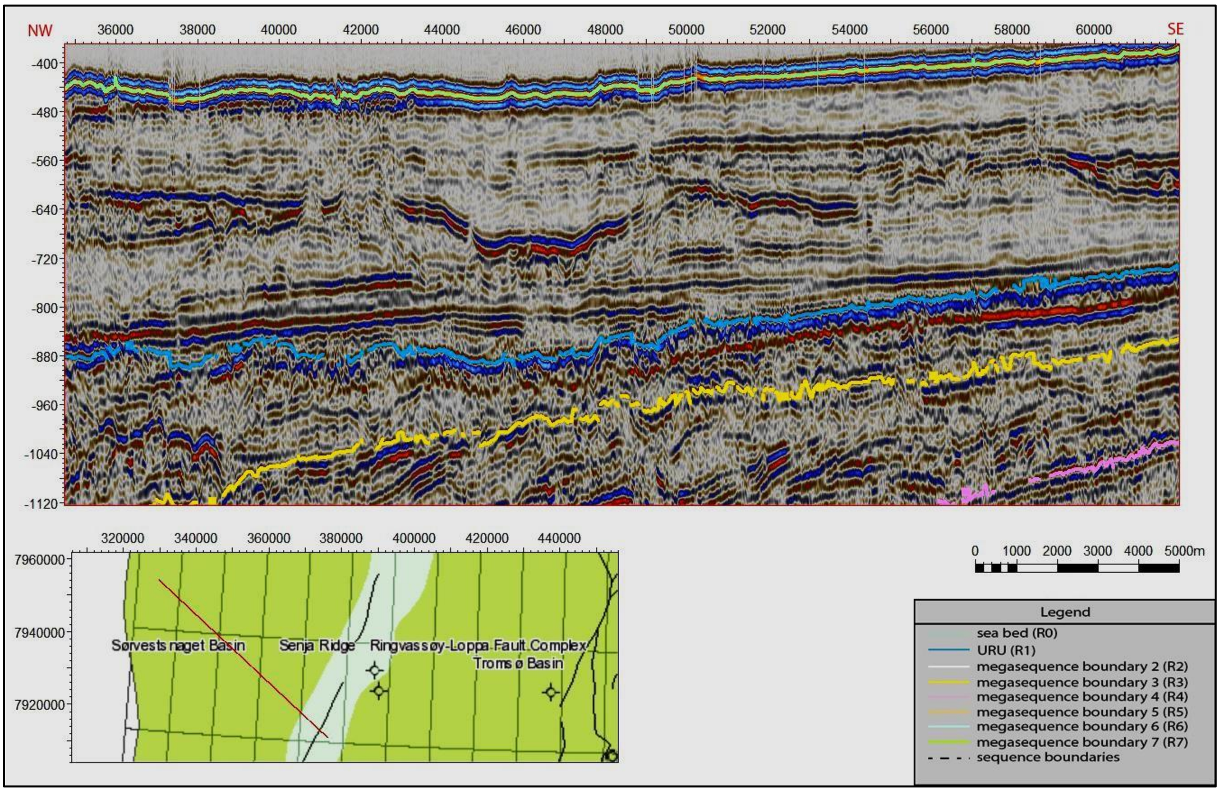

Figure 4.31.Erosional channel within the GIII glaciomarine unit.

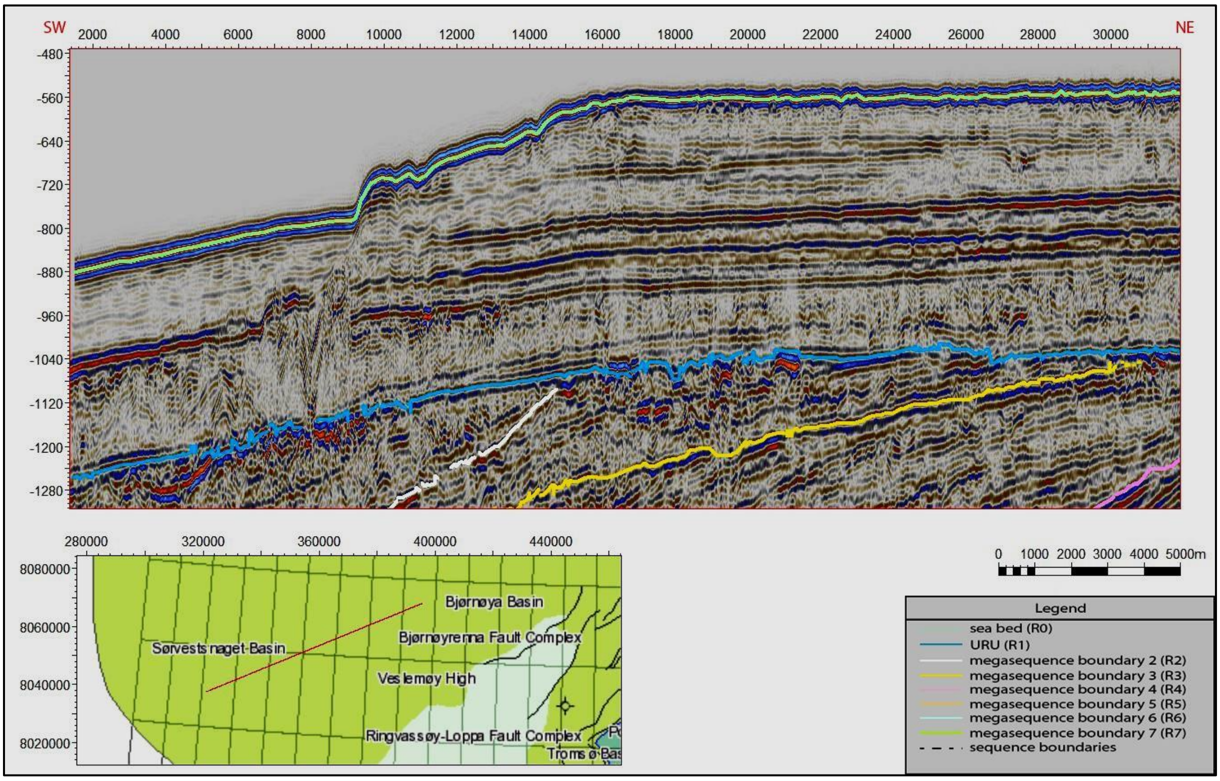

Figure 4.32.GIII glacial unit is characterized by aggradational stacking pattern and weak progradational towards the SW part of this section. Westwards chaotic reflectors are observed.

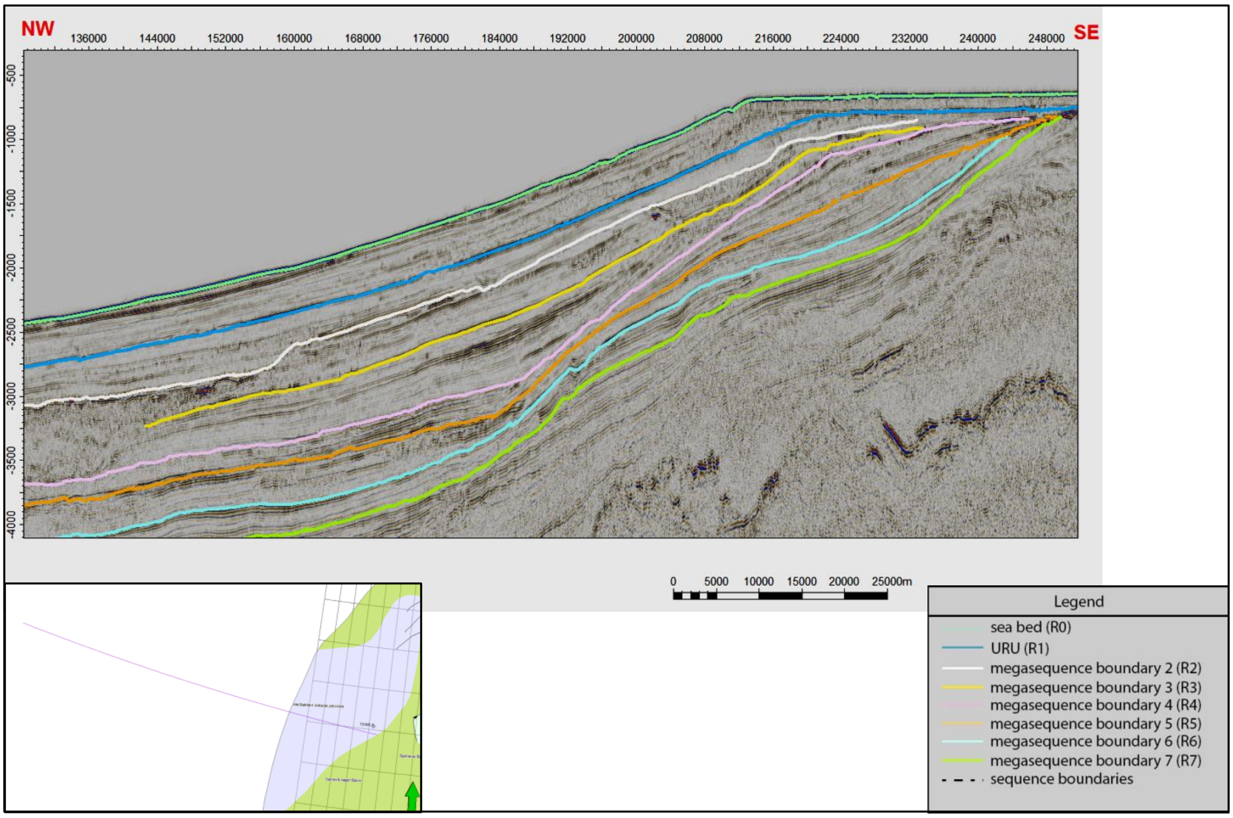

Figure 4.33. In the outer part of the Bjørnøya Fan the reflection configuration pattern of the sequences tend to become parallel to subparallel or is disturbed by mass wasting slides. In these cases the further subdivision of the megasequences into sequences becomes impossible.

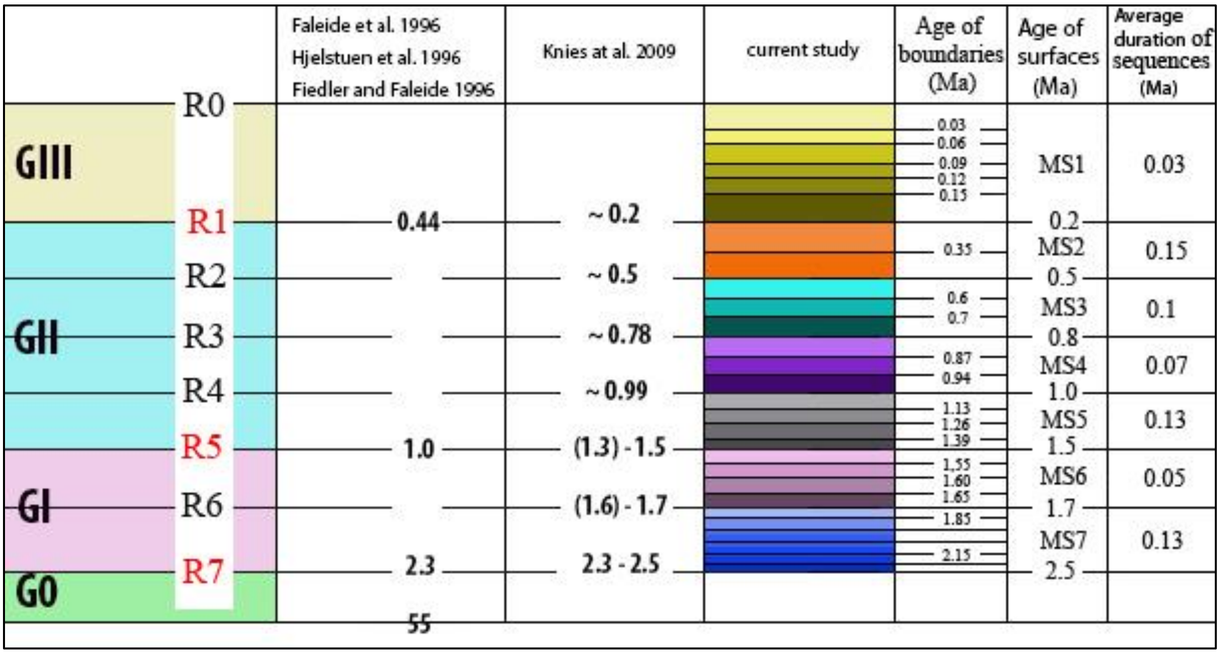

Figure 4.34.Correlation table with relative ages of the surfaces that were identified and interpreted during the current study.

5. Discussion

In this chapter an evaluation of the identified and interpreted seismic sequences will be done (see also Chapter 4). The following topics will be discussed:

- relative chronology of identified sequence boundaries based on the maximum number of identified sequences and ages of megasequence boundaries published in literature;
- correlation between the study area, the mid-Norwegian Continental shelf and Iceland, based on identified glacigenic sequences in each cases and the $\delta^{18}O$ isotopic ice-rafted debris (IRD)records from the deep sea basin; and
- sequences in terms of glacigenic cycles, including processes and controlling factors of the development of the recorded sequences in the SW Barents Sea continental shelf.

5.1 Identified sequences as representing glacial cyclicity

As it was presented in Chapter 4, three glaciomarine units, 7 megasequences and 28 sequences were identified and interpreted in the Bjørnøya Fan during the current study. In general, the glaciomarine sediments of the GI and GII units are characterized by progradational stacking pattern. The GII unit is separated from the GIII unit by the URU (R1). The glaciomarine sediments above the URU are characterized by aggradational stacking pattern and in some cases by weak progradational pattern. The GI and GII are pinching out towards the eastern part and are truncated by the URU (R1). The ages of the megasequence boundaries published in literature and the maximum number of identified sequences within each megasequence were used for the chronology of the sequence boundaries. The results were presented in Figure 4.1.

The age of the URU is not easy to be determined because of the nature of the boundary. The URU was formed as grounded ice sheets cyclically approached and moved across the SW Barents Sea continental shelf to the shelf edge during Pleistocene time. The cycles also include intervals of deposition and retreat of the glacial sheets. For this reason it is not easy to evaluate the duration of the hiatus. The different ages for the URU that have been published in the literature (see correlation table in Fig. 4.1) are with uncertainties and vary from 0.44 to 0.2 Ma.

Each seismic sequence theoretically represents a glacial cycle. These seismic sequences are repeated through the whole Bjørnøya Fan. The deposition of individual sequences is related to the advance of a glacier ice sheet to the continental shelf edge, followed by retreat, glacioeustatic sea level rise and deposition of interglacial mud or clay, before the next advance of glacial ice sheet of the new glaciation. The main “building blocks” of the Bjørnøya Fan is the glacigenic debris flows (GDF). GDFs are a unique mid-to high latitude form of debris flow. It has similar characteristics with fluidized, liquefied, and classified debris flows. The most important difference between these debris flows and the GDFs are the extremely long distances (more than 100 km) that they can move in a very low slope gradients (<1°) (Taylor et al. 2002).

The Bjørnøya Fan was altogether affected by the Plio-Pleistocene northern hemisphere glaciations, with altogether 28 glacial events, some of which may represent stadials.

5.2 Correlation between the study area and glaciations recorded on Iceland and the Mid-Norwegian continental shelf and in deep sea basins

In this subchapter, a correlation between the study area, the mid-Norwegian Continental shelf and Iceland, based on identified glacigenic sequences in each areas, and the $\delta^{18}O$ isotopic and IRD records from the deep sea basin, will be attempted.

In the correlation table in Figure 5.1, the SW Barents Sea continental shelf is correlated to Iceland (Geirsdóttir et al. 2006), Mid-Norwegian continental shelf (Sejrup et al. 2005, Hafeez 2011) and the $\delta^{18}O$(Dahlgren et al. 2005) and IRD (Jansen et al. 2000) curves from the deep sea basin.

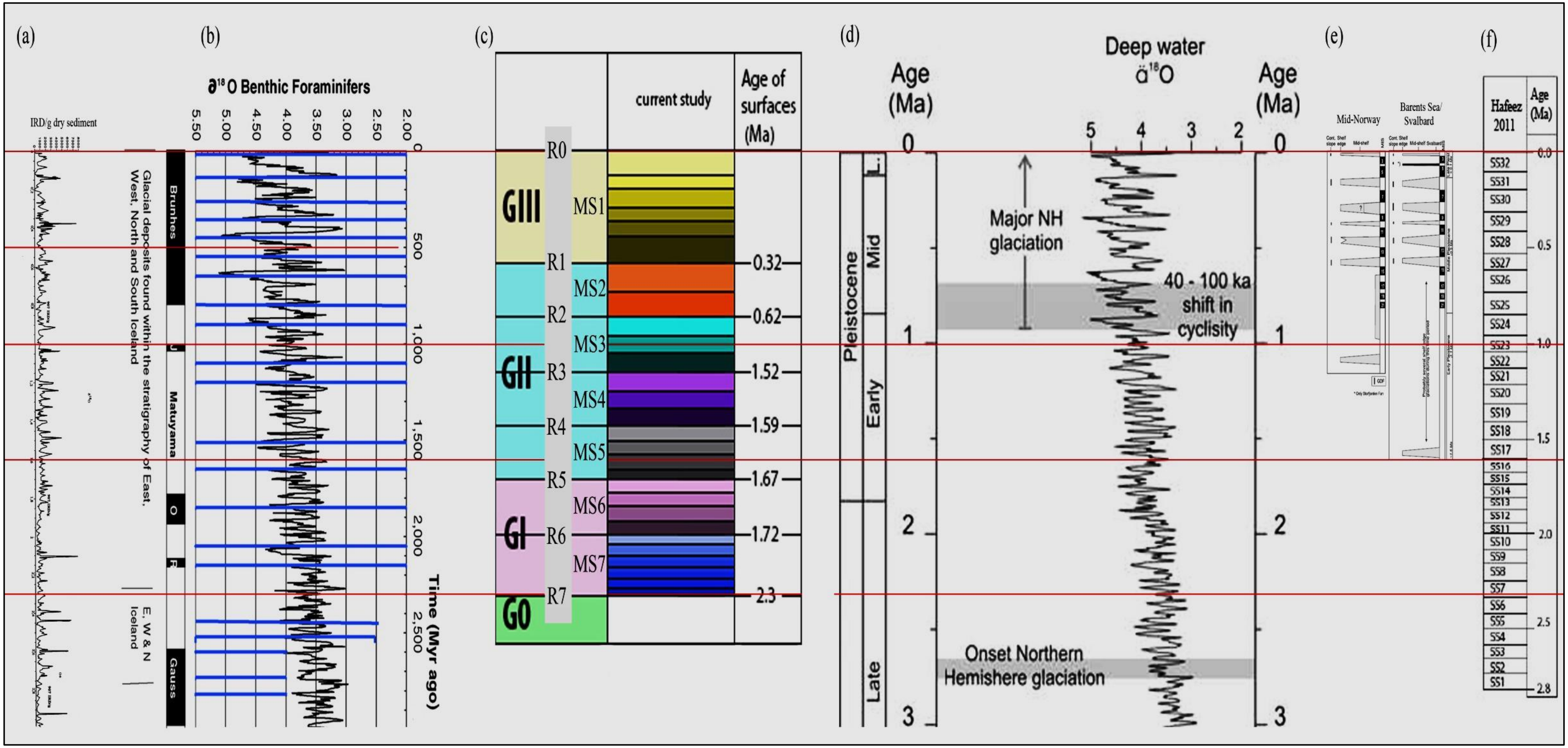

Figure 5.1.Correlation of the identified sequences in the study area (c) with Iceland and Mid-Norway continental shelf. (Modified from (a) Jansen et al. 2000, (b) Geirsdóttir et al. 2006, (d) Dahlgren et al. 2005, (e) Sejrup et al. 2005 and (f) Hafeez 2011). IRD (a) and δ^{18}O (d) curves are correlated with the identified sequences in Iceland (b), Mid-Norwegian continental shelf (f) and SW Barents Sea continental shelf (c). In (e) the known advances of glaciers in Mid-Norwegian and Barents Sea/ Svalbard continental shelf are shown.

5.2.1 Comparison with the Mid- Norwegian continental shelf

There are major differences in the geological setting between the Barents Sea Fan and the Mid-Norwegian continental shelf. One main difference between these two areas is the geomorphological setting and size of drainage area. The Mid- Norwegian ice sheets moved directly from high mountains in mainland Norway down to a rather narrow coastal lowland area that fronted an up to several hundred meters deep basin with high accommodation space, in contrast to the very large shallow shelf or lowland area in the Barents Sea region, from which glacial ice sheets were fed and advanced to the Bjørnøya Fan area that was exposed to a wide oceanic seaway (see Chapter 2). The deep basin located directly off the mid-Norwegian coast was structurally protected by dome structures, sheltering glacigenic deposits from being eroded by strong oceanic currents, as contourite currents. Another difference is related to glacial till composition. The till debris on the Mid-Norwegian continental shelf has mainly been derived from hard crystalline rocks of mainland Norway, in contrast to most of the till material on the Bjørnøya Fan that was sourced in soft rocks in the Barents Sea region. This difference in composition resulted also in different configuration pattern within seismic sequences identified in these areas.

According to Dahlgren et al. (2002) the relative sea level is an important factor for the potential for ice-sheets to advance across continental shelves. Ice thickness, water depth and changes in relative sea level will determine the ability for ice sheets to deposit and further advance across morainal banks or grounding-line, or grounding zone wedges. In order for glaciers to be able to advance to the shelf break the accumulation of morainal banks/ zone wedges are important mechanisms to deposit sediments into lows in the relief of the sea bottom, reducing in that way the accommodation space (Dahlgren et al. 2002).

Accommodation space and water depth is thus controlled by (1) sediment supply, (2) magnitude of glaciation, (3) eustasy, (4) basin subsidence and (5) other factors. In turn, the interaction of these factors determines whether a glacier ice sheet will advance to the shelf break, or not. Hypothetically, a glacier cannot advance into a relatively deep water basin beyond the shelf break, due to calving and ice berg production at the ice margin. However, there are processes that allow the glacier ice sheet to provide its own "road bank" by depositing sediments into transverse troughs. However, such sediments may be eroded if the ice flux either is sustained or increased causing eroded sediments to be dumped over the shelf edge (Dahlgren et al. 2002).

In a summary, coastal morphology, contrast in altitude and lateral extent of upland areas for glacier ice sheets and morphological character of the deep sea adjacent to the shelf area are the main differences between the Mid-Norwegian and the southwestern Barents Sea continental shelves.

The number of sequences interpreted to be of glacigenic origin on the mid-Norwegian continental shelf is according to Hafeez (2011) and Talat (2012) 32. This high number reflects a high degree of preservation of glacigenic sequences. This may have been caused mainly by the relatively short and direct glacier ice flow from high-altitude accumulation areas for the continental ice down to a rather deep basin with high accommodation space, sheltered from oceanic currents, reworking and erosion.

5.2.2 Comparison with Iceland

Geirsdóttir et al. (2007) suggested that Iceland has experienced over 20 glaciations of different intensities, during the last 4-5 Ma (Figure 5.2).In contrast to Norway and Scandinavia, most of the glacial deposits in Iceland are preserved in a continental setting, preserved between lavas and volcanic ash beds. Ice sheets also moved onto the shelf surrounding Iceland, but the glacigenic stratigraphy here is poorly known, as compared to that within the volcanic pile on mainland Iceland.

The glacial cycles in Iceland cannot directly be correlated with the glacigenic cycles encountered in the Bjørnøya Fan. For the Bjørnøya Fan there are uncertainties concerning the chronology of the meagasequence boundaries. These uncertainties influence also the chronology of the sequence boundaries. However, the minimum number of 20 ice ages in Iceland, documented from exposed till deposits, are in accordance with the about 30 glacial events that can be inferred both from the Barents Sea fan and from the mid-Norwegian continental shelf.

The glacial record from the Bjørnøya Fan, the mid-Norwegian continental shelf and Iceland can all be indirectly correlated via deep sea $\delta^{18}O$and IRD records (Figure 5.1). This is discussed below.

5.2.3. Correlation with Deep Sea $\delta^{18}O$ and IRD records

From deep sea basins oxygen isotopes can contribute significantly in the reconstruction of the Pleistocene glacial history. The sediments in the deep sea basin are well preserved, and the variations in climatic changes are recorded from variation in the $\delta^{18}O$ content in calcite. The main principal, in $\delta^{18}O$, is the following: If the ocean is depleted in ^{18}O because of melting of major ice sheets, the $\delta^{18}O$ of calcite is light. One important pitfall of this methodology that should be taken into consideration during the interpretation is that the $\delta^{18}O$ composition of calcite is also dependent on water temperature itself and salinity. For that reason the oxygen isotope curves should be correlated with the sequence stratigraphic record of eustasy (Abreu and Anderson 1998).

The IRD is believed to represent the flux of melting icebergs originating from glaciers large enough to calve in the ocean. The most important factor for their formation is the availability of calving icebergs that can release their sediment contents upon melting in the ocean. Although availability of calving icebergs is highly related to the supply rate (i.e. local ice extent), sea surface temperature and current directions also to some degree influence the supply of icebergs and melting rates (Jansen et al. 2000).

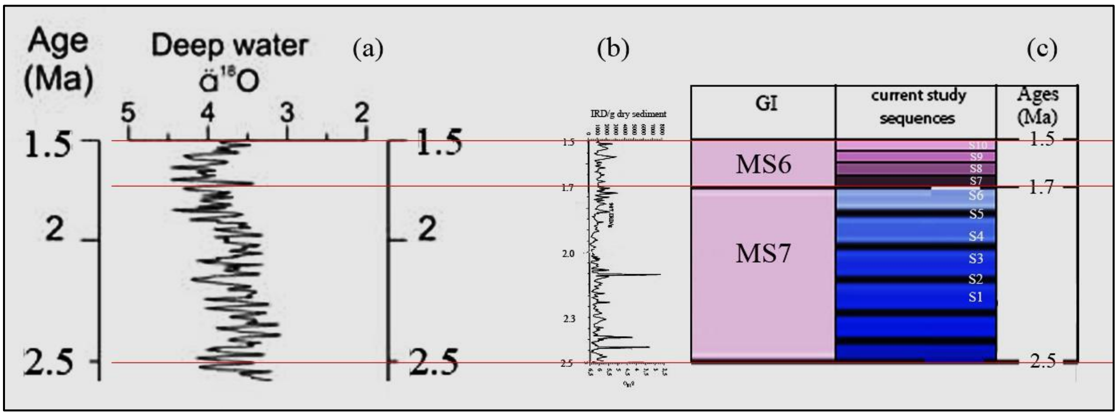

Figure 5.2. Correlation between the megasequences and sequences within the GI glaciomarine unit (c) and the IRD curve (b)(modified from Jansen et al. 2000) and the $\delta^{18}O$curve from deep sea basin (a) (Modified by Dahlgren et al. 2005)

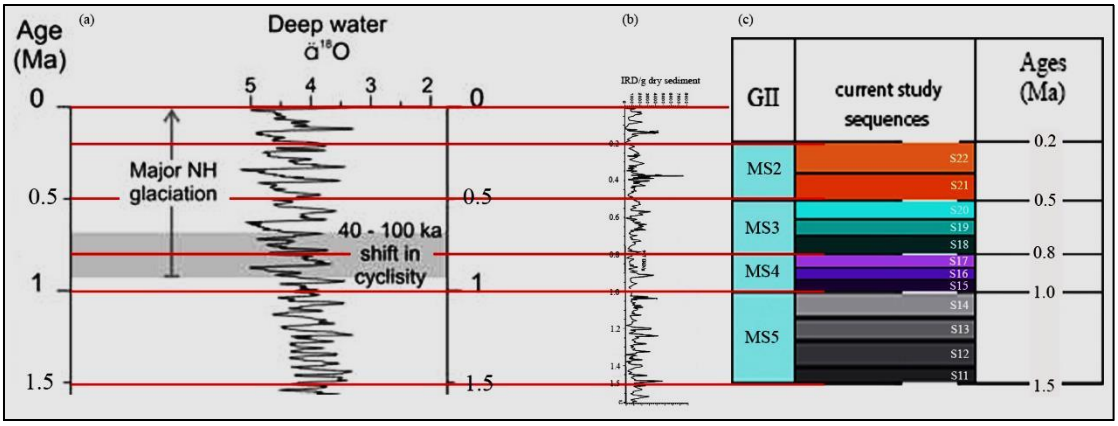

Figure 5.3. Correlation between the megasequences and sequences within the GII glaciomarine unit (c) and the IRD curve (b)(modified from Jansen et al. 2000) and the δ^{18}Ocurve from deep sea basin (a) (Modified by Dahlgren et al. 2005)

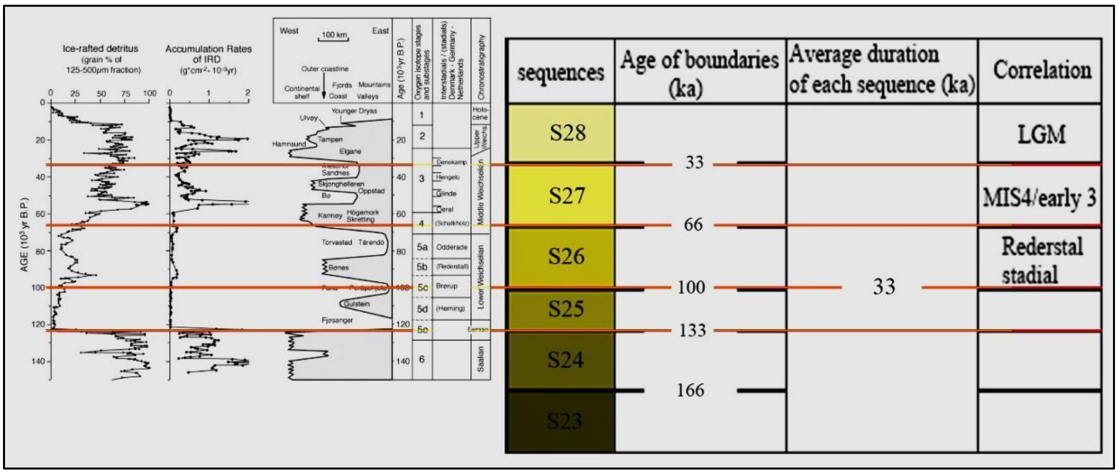

Figure 5.4. Correlation between the megasequences and sequences within the GII glaciomarine unit and the IRD curve (Modified from Mangerud 2003).

In the figures 5.2, 5.3 and 5.4 correlation for each glacial unit is shown separately. In Figures 5.2 and 5.3a shift in the frequency of the IRD can be observed. Within GI the IRD is characterized by lower frequency compared to the sequences of the GII glaciomarine unit. During the GIII glaciomarine unit the available data are of better resolution, resulting in more accurate comparison between the IRD record and the interpreted seismic data. Within each sequence variations in the IRD curve can be observed. The sequence boundary between S24 and S25 fits very well with the shift from high frequent changes in IRD activity to lower.

5.3 Depositional processes and depositional model

5.3.1 Sediment transport and depositional processes

Glaciers are separated into melt-water base glaciers (wet-base glaciers) and cold-base glaciers (glaciers frozen to their substratum or basement). Clastic debris like boulders, blocks, gravel, sand, silt and clay particles are picked up from the substratum by moving melt-water base glaciers and are transferred to the depositional basin englacially. In this way ice-streams are generated.

In general, ice- proximal environments are very dynamic, and sedimentary successions formed in these settings consist of heterogeneous facies types characterize by lateral and vertical facies variations, and irregular bed geometries. (Eyles and Eyles, 2010).The composition of the glacial debris depends on the lithology of the bedrocks. The glacial advances on the shelf are recorded by deposition of till deltas (Figure 5.6) (Sejrup et al. 2005). These poorly sorted basal debris issuing from the ice front at the grounding line (where the ice begins to float) (Eyles and Eyles, 2010) can be remobilized moving downslope as debris flows, and can contribute to the build- up of grounding- line fans (Wohlfarth et al. 2008, Eyles and Eyles, 2010).

According to Nyland et al. (1992) more than 1000m, of bedrock has been eroded from the SW Barents Sea continental shelf during the Cenozoic. A major part of the erosion is glacial and was caused by fast-flowing ice streams draining through the Bjørnøya Trough to the shelf break, delivering sediments to the Bjørnøya Fan (Andreassen et al. 2007). Andreassen et al. (2007) observed that periods of slowdown or quiescence were followed by reactivation of fast flow ice sheets during several glaciations. This can be an explanation for the six sequences observed within the GIII glaciomarine unit.

According to Laberg et al. 2013, the average rate of glacial erosion in the SW Barents Sea the last ca. 2.7 Ma was varying (Figure 5.5). Possible to these variations the Bjørnøya Fan is divided into three glaciomarine unit GI, GII and GIII, each one of these representing a separately stage of development. This will be discussed below.

Many factors determine the formation, deposition and preservation of the glacigenic sequences. And yet not all sequences that were formed appear to have the same evolutionary history within the Bjørnøya Fan. The preservation potential changes from place to place and depends on many factors. All these factors will be discussed in detail further in this chapter. One single glacial cycle should not be awaited to have been represented by a uniform deposit over the whole fan area, due to variation in space and time of the glacier ice dynamics. At some periods the ice sheets may have been erosive and at other periods no-erosive, depositional or/and floating. The frequency of glacial-interglacial intervals may also have changed through time. In the current study, the average duration of each of the identified megasequences in the Bjørnøya fan varies (see Figure 4.34). There is a cyclicity in the average duration of each megasequence with a systematically increase and decrease of the average duration. These variations can represent smaller variations within separately glacial cycles. Variation in glacial frequency may have caused changes in the architecture style of the seismic sequences.

The Bjørnøya Fan is characterized by a line source and this plays an important role in the distribution of sequences within the Bjørnøya Fan. The time- thickness maps for the megasequences and the glaciomarine units (Figure 4.14) show the differences sequence distribution and shift in position of depocenters. Then main depocenter during the GI glaciomarine unit was located approximately in the basinward part of the Bjørnøya Fan between 72°30’N and 71°15’N. There were also smaller depocenters in the area between 74°00’N and 73°15’N.

The maximum thickness of the GI was approximately 1000 ms. During the deposition of the GII glaciomarine unit the depocenter had expanded and covered the western part of the Bjørnøya Fan with its thickest deposits located in the area south of 73°00’N. The maximum thickness of the GII is approximately 1750 ms. According to Laberg et al. 2012 during the deposition of GII glaciomarine unit the source area was characterized by high glacial erosion, estimated to be more than approximately 0.6 mm/yr (Figure 5.5B).

The conditions in the Bjørnøya Fan changed during the deposition of the GIII unit. The depocenter had shrinked in extent and a part of the older depocenter during the GII was still active with thinner deposits, restricted in the area between 73°30’N and 72°15’N. In addition, a second depocenter south of the first one was located between 72°00’N and 71°40’N. The thickness of the deposits here are up to ~ 750 ms.

Sequences in these two depocenters of the GIII glaciomarine unit are characterized by weak progradational reflection patterns towards the west (basinwards) (Figure 4.14). These changes are shown in more details in the time-thickness map for each megasequence (Figures 4.15 and 4.21). The GI is characterized by restricted depocenters. To conclude, the time-thickness maps are very useful to visualize the effect of repeatable glacial cycles in the continental shelf and the development of the Bjørnøya Fan, and therefore changes of depocenters through time.

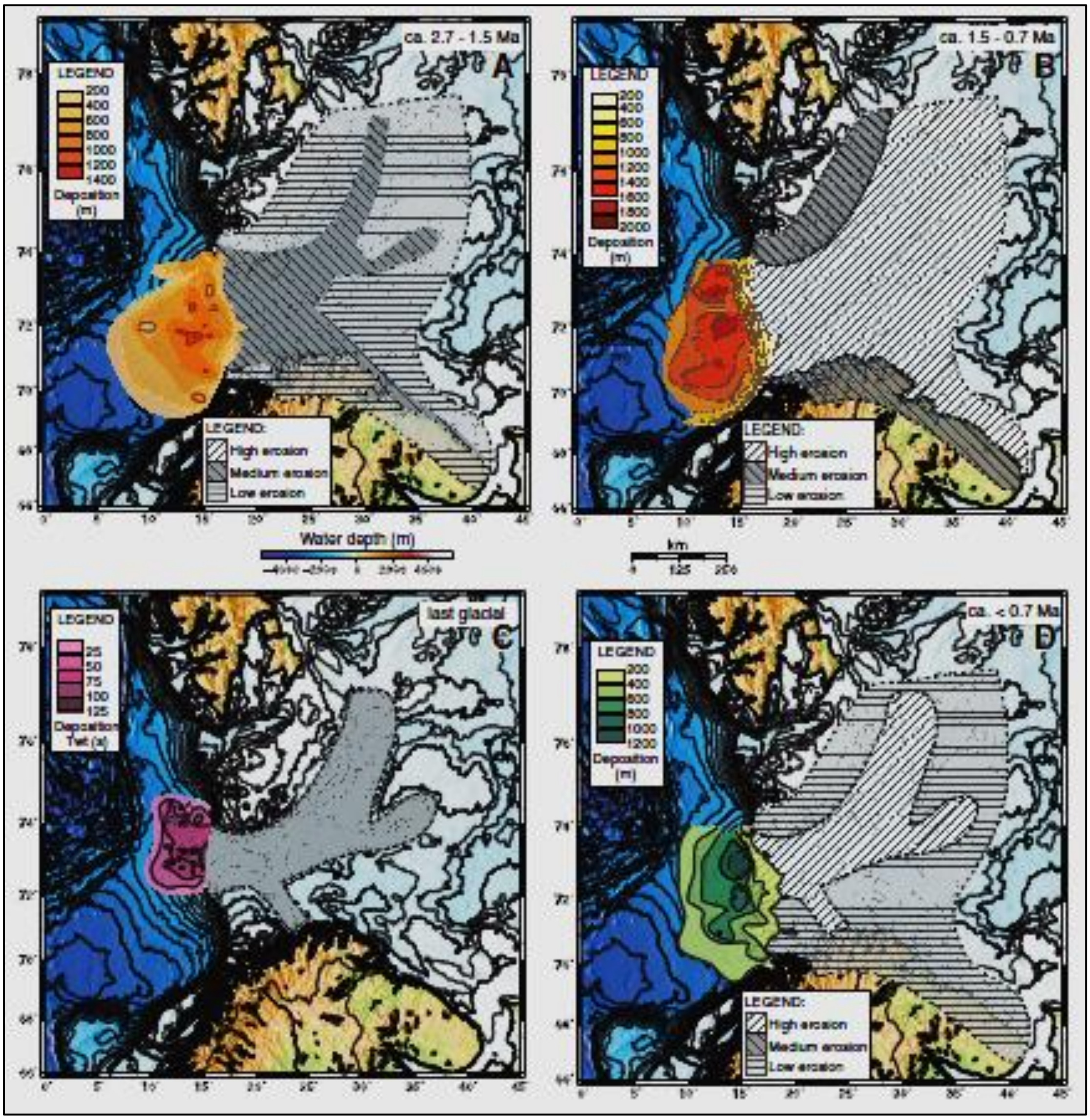

Figure 5.5. (A) The areas characterized by glaciofluvial erosion during the period from ca. 2.7 to 1.5 Ma are indicated, and a glaciofluvialdrainage system located in the inner part of the present troughs is tentatively outlined. The isopach of the erosional products is also shown (the isopach is from Fiedler and Faleide, 1996). (B) The area where glacial erosion is inferred to have been high during the period from ca. 1.5 to 0.7 Ma is indicated. The rest of the drainage area is inferred to have experienced less erosion. The isopach of the erosional products is also shown (the isopach is from Fiedler and Faleide, 1996). (C) Bathymetric map of the southwestern Barents Sea, including the isopachof the glacigenic sediments deposited on the Bjørnøya Fan during the latest two glacial maxima (from Laberg and Vorren, 1996). These sediments are inferred to have been eroded mainly by paleo–ice streams located in the adjacent troughs Bjørnøyaand Ingøydjupet (indicated by gray tones). (D) Bathymetric map of the southwestern Barents Sea shelf. The areas where glacial erosion is inferred to have been high during the period from ca. 0.7 Ma to present is indicated, i.e., in the troughs Bjørnøya and Ingøydjupet, where paleo–ice streams were located during glacial maxima. In the rest of the drainage area, erosion was low. The isopach of the erosional products is also shown (the isopach is from Fiedler and Faleide, 1996). In areas of high, medium, and low erosion, the rates were estimated to >~0.6 mm/yr, between ~0.15 and 0.6 mm/yr, and <~0.15 mm/yr, respectively. Twt—two-way traveltime (Laberg et al. 2012).

The evolution of the glaciomarine units was strongly influenced and controlled by available accommodation space. The two main factors that influence the accommodation space are glacioeustacy and subsidence. Even though the tectonic uplift is a prerequisite for the wedge growth off the western Barents Sea, according to Butt (2000) the climate is considered as the main factor behind the wedge growth as observed from 2.6 Ma. Total subsidence is a function of tectonic subsidence and subsidence due to sediment compaction.

The tectonic subsidence is related to the opening of the Norwegian-Greenland Sea in the early Cenozoic due to which the SW Barents Sea margin is characterized by megashear zones and rifted segments (Faleide et al. 1996). Rift flank uplift was part of this tectonic evolution (Laberg et al. 2012). The sediment compaction is related to the composition of the glacial till or other glacially derived sediments in the fan area. The lithological composition is directly related to the geology of the source area (drainage area). Tills and debris flows derived from primary till deposits are in the Bjørnøya Fan succession mainly consisting of fine-grained material, such as clays (see above). However, the Vestbakken Volcanic Province was during Pleistocene dominated by sandy till material (Knutsen and Larsen 1996 in Ryseth et al. 2003).Lateral variations in sediment composition thus may imply that the compaction have varied through time, hence the accommodation space. A higher rate of sedimentation of till in areas with high accommodation space can have resulted in better acoustic contrast and therefore stronger reflectors (Figure 4.4).

5.3.2 Depositional model

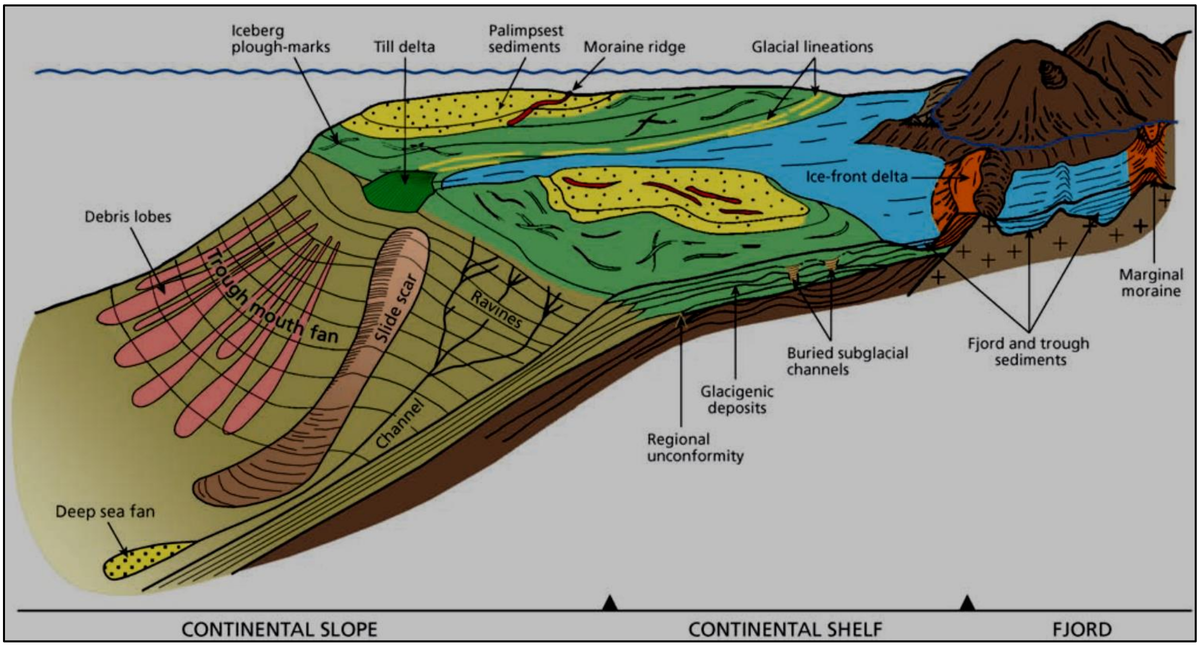

Figure 5.6. Model showing the main glacigenic morphological elements and lithofacies of the Norwegian continental margin, exemplified by the margin off of northern Norway; modified after Vorren and Mangerud (2006).(Wohlfarth et al. 2008)

The depositional model for glaciomarine environments by Vorren and Mangerud (2006),modified by Wohlfarth et al. (2008) (Figure 5.6),has been applied for the discussion and interpretations of processes and depositional environment. The onset of the glacial deposition in the Bjørnøya Fan is related to the formation of the glacial feeder system of the Bjørnøya Trough system. The ice sheet had to extend across the continental shelf and reach the shelf break, and the troughs had to be developed so they could function as drainage routes for ice streams.

The location of the Bjørnøya Trough was probably controlled by a pre-existing topography. The troughs are likely to be found where preglacial fluvial or glaciofluvial channels existed, as has been reconstructed for the Barents Sea shelf (Vorren et al. 1991, in Vorren and Laberg 1997). According to Vorren et al. (1991) the glacial drainage area for the Bjørnøya Fan is set to 576,000 km^2. Within the drainage area two large systems have been observed: the southern system that follows the channels outside the coast of northern Norway, and the main system that follows the Bjørnøya Trough (Fiedler and Faleide, 1996).

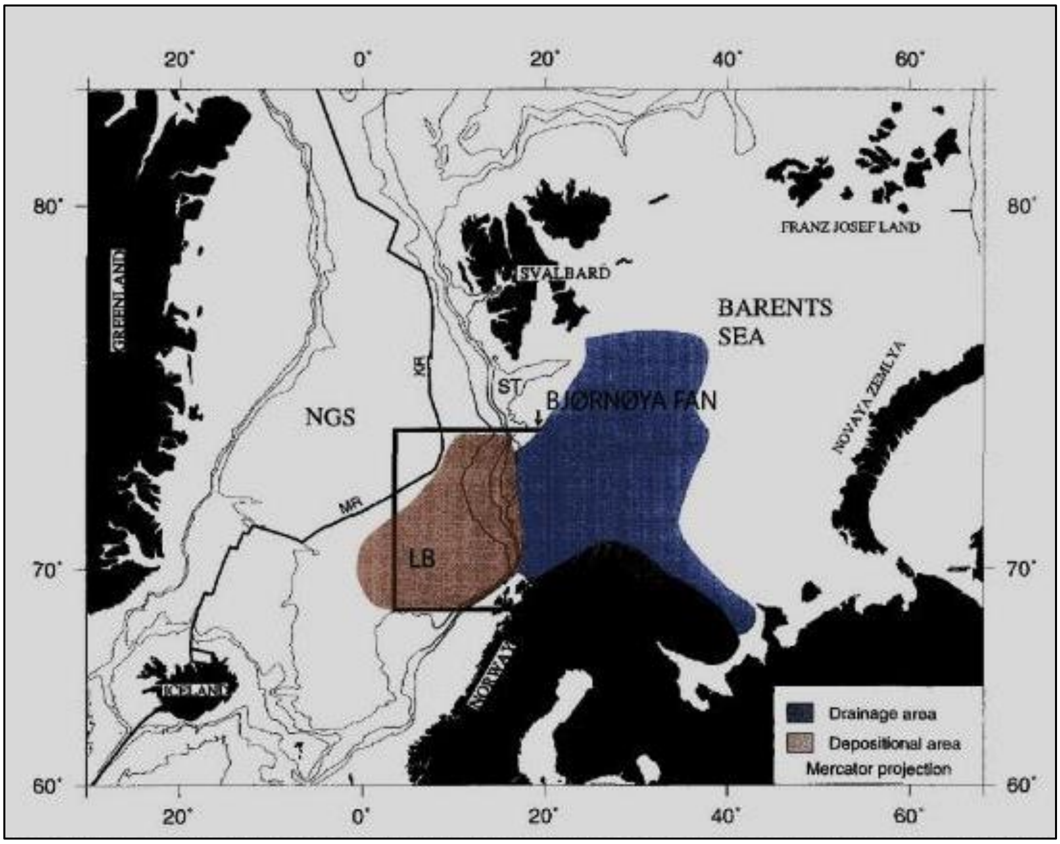

Figure 5.7. The drainage area of the Bjørnøya Fan is shown together with the Bjørnøa Fan (bounded by the black rectangular) (modified from Fiedler and Faleide 1996).LB: Lofoten Basin, NGS: Norwegian- Greenland Sea.

The stratigraphy of the Bjørnøya Fan can be divided into a younger glacially dominated debris flow facies (GII and GIII glaciomarine units) and an older facies which contain glacigenic sediments, but is far less dominated by glacial debris flows (GI glaciomarine unit) (Vorren and Laberg 1997).In the map presented in Figure 5.8the main ice streams during the Last Glacial Maximum (LGM) are presented. In general, the glaciomarine units and the megasequences are mappable in the whole study area.

The number of identified sequences within each megasequence is not constant in every seismic section. This can be explained by the fact that the Bjørnøya Fan development, due to interplay of morphology and glaciology, was asynchronous and non-uniform.

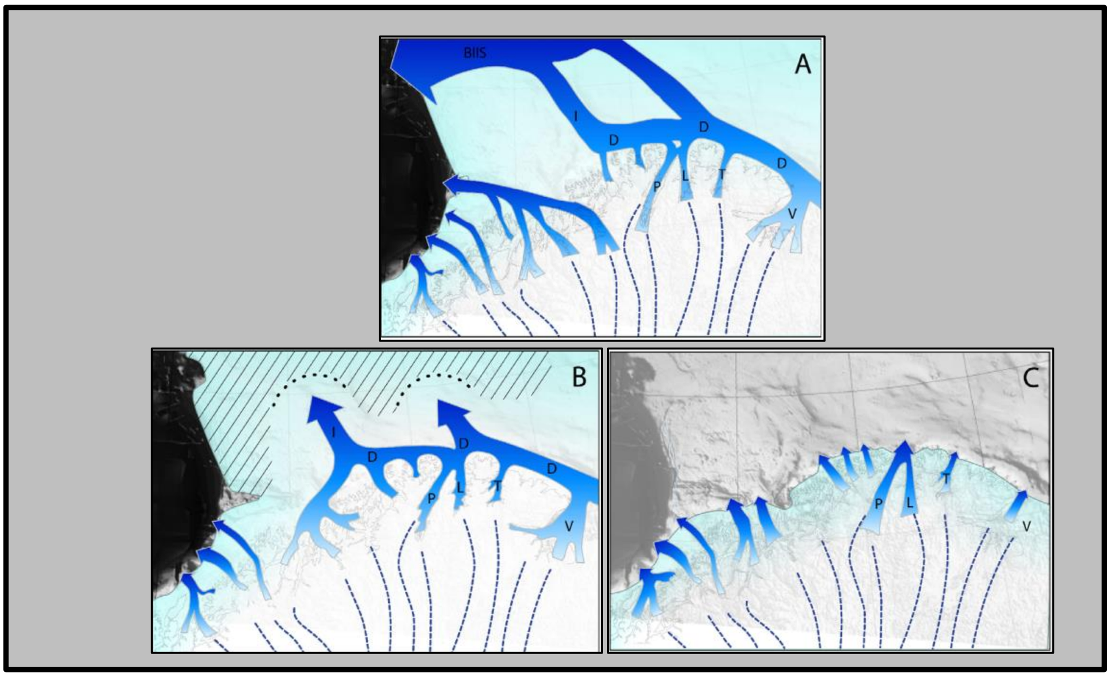

Figure 5.8. Preliminary reconstruction of ice-sheet dynamics based on thesea-floor glacial geomorphology. Three time-steps are shown to represent the LGM (A), an intermediate stage (B) and a coastal stage (C)which probably represents a diachronous ice margin position at around15-^{14}CBP. Stippled lines indicate generalized flow patterns on the mainland (e.g. Olsen et al., 1996b). BIIS, Bear Island Trough Ice Stream; I, Ingøydjupet; D, Djuprenna; V, Varangerfjorden; T, Tanafjorden; L, Laksefjorden; P, Porsangerfjorden. Dotted lines in (B)indicate position of lobate ice-stream margin and shaded area marks adisintegrating body of ice or open sea distally to the active ice in the S–SE. (Modified from Ottesen et al. 2008)

5.3.2.1 GI glaciomarine unit

The GI glacial unit is mainly characterized by acoustically laminated facies with prograding westward wedges. According to Dahlgren et al. (2005), these seismic facies have commonly been related to normal marine and glaciomarine hemipelagic sedimentation, variably affected by contour currents. These deposits can be interconnected with individual and/ or amalgamated glacigenic debris flows. Also the buried subglacial channels that are recorded in some of the seismic sections are interpreted to have beenrelated to ice stream or melt water from the retreating ice sheet. In the GI unit the majority of the offlap breaks are eroded, that can be explained by relative sea level drop and the erosional action of ice streams and ice sheets, as described from the mid-Norwegian shelf (Talat 2013).

In general, the GI unit contains glacigenic sediments, but the unit is much less influenced or dominated by glacial debris flows (Vorren and Laberg 1997). MS7 is mainly characterized by tangential oblique and in some sections by sigmoid propagational configuration. The oblique tangential propagational configuration pattern is related to grounded ice sheet in the shelf, causing the erosion of the topset beds and in most of the cases of the offlap breaks.

Sigmoidal propagational configuration pattern is thought related to floating ice sheets where offlap breaks are preserved, but not topset beds (Hafeez 2011). The GI unit is interpreted as shelf- margin, glacifluvial to glaciomarine sediments (Andreassen and Winsborrow 2009). In that way, GI can be characterized as a transition from glaciofluvial to glaciomarine depositional environment.

5.3.2.2 GII glaciomarine unit

The GII glaciomarine unit is characterized by a chaotic reflection pattern that indicates large-scale mass-movement deposits related to slumps and slides. These deposits are characteristic for slope facies (Andreassen and Winsborrow 2009). The development of the R5 megasequence boundary marked a change in the depositional environment. This change is correlated to the megaslides described by Hjelstuen et al. (2007). The GI and GII units are separated by the R5 boundary. The R5 marked a change in the depositional environment, correlated to megaslides. The age of R5 (~1.5 Ma) is correlated to the onset of repeated major ice sheet expansion to the shelf edge after about ~1.2 Ma ago. These ice sheet expansions are related to a continued debris flow activity and mega slides along the western Svalbard-Barents Sea margin (Knies et al. 2009).In Profile 4 (Figure 4.9), the offlap breaks and the topsets are preserved and they are characterized by an ascending (positive) offlap break trajectory. The ascending offlap break trajectory indicates floating of the ice sheet caused by rise of the sea level beyond the limit of the buoyancy, accompanied by a high rate of sedimentation. As mentioned In Chapter 4, erosional channels can be observed along the R5 seismic boundary and upwards. This change is inferred to be related to the onset of an increase in global ice volume that characterizes the mid-Pleistocene transition at ~0.94 Ma (Mudelsee and Stategger 1977, in Knies et al. 2009). This transition is associated with a 20-30 m drop of the sea level (Kitamura and Kawagoe in Knies et al. 2009).

As also described in Chapter 4, the GII glaciomarine unit in many seismic sections is characterized by acoustically transparent, chaotic and structureless reflection configuration pattern. This reflection configuration represents what is commonly referred to as glacigenic mud or debris flows. Their origin is related to increased sediment supply. Higher sedimentation rates can generate sliding, slumping and mud diapirs (Talat 2012). Usually, more than one debris flows in conventional seismic appear as a single acoustically transparent body draping the slope. The only indicator for the amalgamated character is the undulating surface topography (Dahlgren et al. 2005). In some of the seismic sections, for example in the Profile 1 (Figure 4.3),the increased thickness of the bottomsets reveals phenomenon of sediment by pass that may be associated with contouritic curents (Dahlgren et al. 2002).The GII unit is characterized by better build up clinoforms compared to the GI unit.

5.3.2.3 GIII glaciomarine unit (sequence 23 to sequence 28)

As it was mentioned in Chapter 4, the MS1 is the youngest megasequence in the Bjørnøya Fan, and it contains sediments deposited between the URU (R1) and the sea bed (R0).A flat offlap break trajectory can be observed in gently prograding to aggradating system tracts and are generated due to low and equal sedimentation rate and accommodation space, as also shown from the mid-continental shelf (Hafeez 2011, Talat 2012). The erosional channels in the MS1 (Figure 4.31) can be correlated to ice streams. The chaotic reflectors within the MS1 (Figure 4.32) can be related to the composition of the glacial tills. These tills are composed mainly of clays and due to high water content they are very sensitive to deformation. Also differential compaction can be caused by differences in glacial till composition. During that period the source area of glacial till was both the mainland of Norway and the eastern Barents Sea (see map in Figure 5.5C, 5.8).

5.4 Stages of Bjørnøya Fan deposition

Based on the interpretation of the seismic sections within the study area, three stages of development can be marked. This division is correlated to the three glaciomarine units.

5.4.1. Stage-1: GI glaciomarine unit

Stage-1 represents the onset of glaciations in the western Barents Sea continental shelf. The stage is characterized by glaciofluvial or glaciomarine sedimentation, interrupted by low frequency events of debris flows. The offlap breaks are mostly eroded. During this stage, glacial expansion to the shelf edge did not occur, and the deposits are found in till deltas (Sejrup et al. 2005).

5.4.2 Stage-2: GII glaciomarine unit

Stage-2 was initiated about ~ 1.5 Ma ago, the same as the age of R5 boundary. The stage is characterized by mass-wasting processes and a continued debris flow activity in the western Barents Sea margin. The shift from stage-1 to stage-2 is marked by the R5 megasequence boundary. The age of R5 (~ 1.5 Ma) is correlated to the onset of repeated major ice sheet expansion to the shelf edge (Laberg et al. 2010, Sejrup et al. 2005), based on the mega-slides caused by the increased sediment supply from the advancing glaciers to the shelf edge (Faleide et al. 1996). In addition to high sedimentation supply, the mega-slides were promoted also by large variations in sediment properties of the muddy glacigenic sediments (Kuvaas and Kristoffersen, 1996 in Laberg et al. 2010. Like the stage-1, also in this stage the deposits are related to till deltas or diamicton aprons. These deposits are consisting of normal marine and glaciomarine hemipelagic sedimentation, variably affected by contour currents. This stage is also characterized by distinct prograding clinoforms. Sigmoid prograding configuration pattern (see Chapter 4)is interpreted to be due to increasing accommodation space. The erosional channels that were observed within GII unit (see Chapter 4) are related to deposition of sediments from channelized melt water discharge (Laberg et al. 2010)

5.4.3 Stage-3: GIII glaciomarine unit

Stage-3 is characterized by low and equal sedimentation rate and accommodation space and during that stage the glacigenic sediments were deposited. It is characterized mainly by glacigenic debris flows that are sourced from a common and homogenous part of the upper fan.

Chapter 6: Conclusions

In the present master thesis, seismic stratigraphy of the Bjørnøya Fan was refined and three glaciomarine units (GI-GIII), seven megasequences (MS1-MS7) and 28 sequences (S1-S28) were identified and interpreted. Based on the 28 identified seismic sequences and the ages of the megasequences published in literature, the sequence boundaries were relatively dated.

Seismic stratigraphic sequence boundaries were applied as the main tool for subdivision of the Bjørnøya Fan. Acoustic impedance contrast between beds above and below the unconformity and along the unconformity has determined the seismic expression of the seismic stratigraphic sequence boundary. In glacial and interglacial successions the boundary between relatively dense glaciomarine till material and overlying interglacial mud to hemipelagic clays of lower density is inferred to have been expressed by high impedance contrast between adjacent bedsets. In glaciomarine depositional environments, the nature of seismic stratigraphic sequence boundaries can laterally change from maximum flooding surfaces (MFS) basinwards to erosional regression surfaces landwards, where the ice sheets have been grounded.

The Bjørnøya Fan was repeatedly affected by the Plio-Pleistocene northern hemisphere glaciations, with altogether 28 glacial events, some of which may represent stadials. Each seismic sequence hypothetically represents one glacial cycle. The sequences are bounded by the same type of sequence boundaries and are characterized by the same architecture style. These packages, the seismic sequences, are repeated through the whole Bjørnøya Fan. The depositional course of each sequence represents one glacial cycle with individual sequences formed by the advance of a glacier ice sheet to the continental shelf edge, followed by ice retreat, glacioeustatic sea level rise and deposition of interglacial mud or clay, before the next advance of glacial ice sheet of the new glaciation

Variations in glaciomarine depositional processes during the last ca. 2.5 Ma are reflected by three stages of development of the Bjørnøya Fan. These three stages are correlated to the three glaciomarine units GI-III. The first stage is correlated to the initiation of glaciations in the Barents Sea continental shelf and represents a transition from pre-glacial to glacigenic sedimentation. The second stage, initiated ~ 1.5 Ma ago, is characterized by distinct prograding clinoforms that are correlated to the onset of repeated major ice sheet expansion to the shelf edge. In the third stage, depositional conditions changed towards glacigenic debris flows that were sourced from a common and homogenous part of the upper fan.

The numbers of glacial cycles in the Bjørnøya Fan can be correlated approximately to the mid-Norwegian continental shelf and Iceland, indicating a similar glacial history during the Late Neogene. Due to variables as geological setting, preservation potential and other factors, only a rough correlation can be achieved, especially for the GI and GII glaciomarine units, where the data are of lower resolution compared to data for the GIII unit.

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